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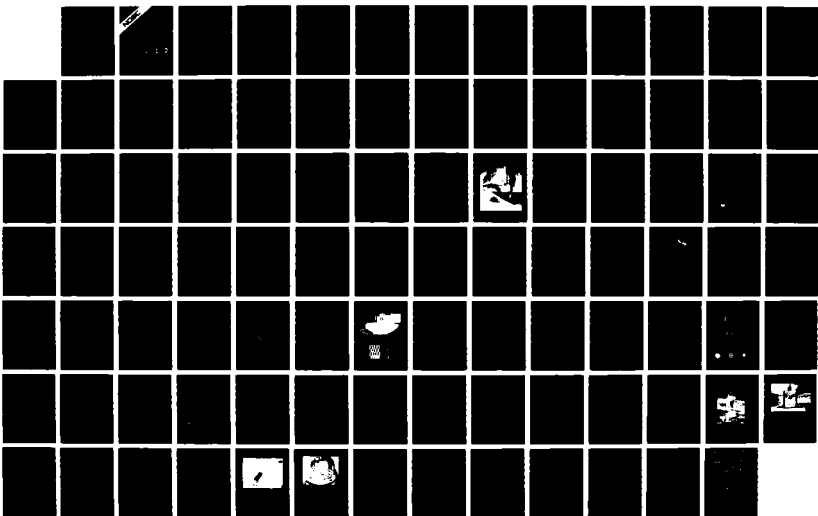
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MOBILE ROBOTS(U) NAVAL OCEAN SYSTEMS CENTER SAN DIEGO
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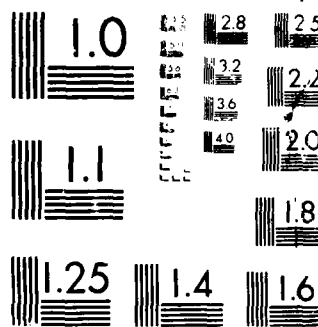
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March 1988

Survey of Collision Avoidance and Ranging Sensors for Mobile Robots

H. R. Everett



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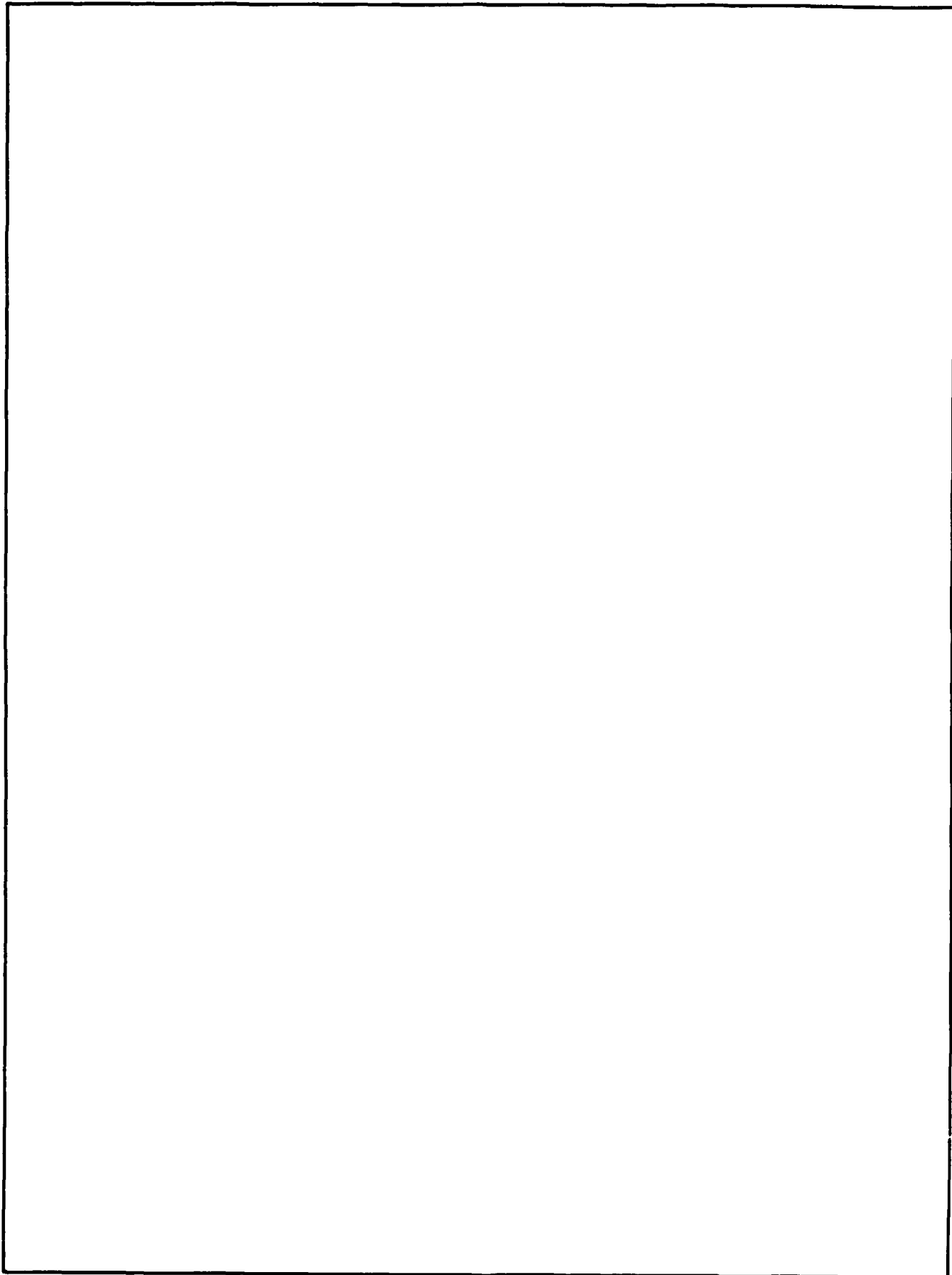
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1.0 INTRODUCTION

The past few years have brought about a tremendous rise in the envisioned potential of robotic systems, and a correspondingly significant increase in the number of proposed applications. In the nonindustrial arena, numerous programs have evolved, each intending to harness some of this promise in hopes of solving some particular application need. Most of these efforts are government-sponsored, aimed at the development of systems for fighting fires, handling ammunition, transporting materials, conducting underwater search and inspection operations, and patrolling warehouses and storage areas, to name but a few. Many of the resulting prototypes, which were initially perceived as logical extensions of the traditional industrial robotic scenarios, have met with unexpected difficulty due to an insufficient supporting technology base.

One such problem area common to many of these efforts arises from the need of a mobile system to interact with the physical objects and entities in its environment. The platform must be able to navigate from a known position to a desired new location and orientation, while at the same time avoiding any contact with fixed or moving objects while enroute. There has been quite a tendency in many cases to oversimplify these issues, and assume that the natural growth of technology will provide the needed solutions. While this ultimately will come to pass, it is important to pace the development of the platform with a parallel development of the needed collision avoidance and navigation technology. Fundamental in this regard, are the required sensors with which to acquire high resolution data describing the robot's physical surroundings, in a timely yet practical fashion in keeping with the limited onboard energy and computational resources of a mobile vehicle.

The difficulty can be directly related to the unstructured nature of the operating environment. Industrial process control systems used in high-volume manufacturing scenarios rely on carefully placed sensors which exploit the target characteristics. Background conditions are arranged to provide minimal interference, and often aid in the detection process by increasing the on-off differential or contrast. The introduction of industrial robots and the accompanying shift towards flexible versus hard automation has led to increasing use of vision systems as opposed to the more simplistic proximity and breakbeam sensors. More intelligent process and quality control decisions are made possible, but at the expense of increased system complexity.

Trying to directly carry this specialized assembly-line technology over into the unstructured world of a mobile robot makes little sense; the problems are fundamentally different. For example, in the collision avoidance problem, the nature and orientation of the target surface is not known with any certainty; the system must be able to detect a wide variety of surfaces under varying angles of incidence. Control of background and ambient conditions may not be possible. Preprogrammed information regarding the relative positions, orientations, and nature of objects within the sensor's field of view becomes difficult indeed for a moving platform. Specialized sensors specifically intended to cope with these problems are needed to provide a mobile platform with sufficient environmental awareness of its surroundings to allow it to move about in a realistic fashion.

Possible considerations for such sensors are summarized below (reference 1):

- a. *Field-of-view*. Wide enough with sufficient depth of field to suit the application.
- b. *Range capability*. The minimum range of detection, as well as the maximum effective range, must be appropriate for the intended use of the sensor.
- c. *Accuracy and resolution*. Must be in keeping with the needs of the given task.
- d. *Ability to detect all objects in the environment*. Objects can absorb emitted energy; target surfaces can be specular as opposed to diffuse reflectors; ambient conditions and noise can interfere with the sensing process.

- e. *Operate in real time.* The update frequency must provide rapid, real-time data at a rate commensurate with the vehicle's speed of advance.
- f. *Concise, easy to interpret data.* The output format should be realistic from the standpoint of processing requirements; too much data can be as meaningless as not enough; some degree of preprocessing and analysis is required to provide output only when action is required, with threat ranking.
- g. *Redundancy.* The system should provide for graceful degradation and not become incapacitated due to the loss of a sensing element; a multimodal capability would be desirable to ensure detection of all targets, as well as, to increase the confidence level of the output.
- h. *Simplicity.* The system should be modular to allow for easy maintenance and evolutionary up-grades; not hardware specific and low in cost.
- i. *Power consumption.* The power requirements should be minimal in keeping with the limited resources onboard a mobile vehicle.
- j. *Size.* The physical size and weight of the system should be practical with regard to the intended vehicle.

Mobile ranging needs can be broken down into the two issues of navigation and collision avoidance. Navigational sensors would require high angular and/or range resolution over fairly long distances, with a relatively narrow field of view. Collision avoidance sensors, on the other hand, would operate over shorter ranges, with less resolution required. The field of view should provide sufficient coverage for a turning vehicle, and allow enough time for the vehicle to stop or alter course.

This document is intended to provide some basic background on the various noncontact distance measurement techniques available (figure 1), with related discussion of their implementation in the acoustical, optical, and electromagnetic portions of the energy spectrum. An overview of candidate systems, both commercially available and under development, is provided, followed by a brief summary of interesting research currently underway in support of the collision avoidance and noncontact ranging needs of a mobile robot.

NONCONTACT RANGING TECHNIQUES		
2.1.1	Proximity	
	2.1.1.1	Break Beam
	2.1.1.2	Reflective
	2.1.1.3	Diffuse
2.1.2	Triangulation	
	2.1.2.1	Stereo Disparity
	2.1.2.2	Active Triangulation
	2.1.2.3	Structured Light
	2.1.2.4	Known Target Size
2.1.3	Time of Flight	
2.1.4	Phase Modulation	
2.1.5	Frequency Modulation	
2.1.6	Interferometry	
2.1.7	Swept Focus	
2.1.8	Return Signal Intensity	

Figure 1. Taxonomy of noncontact ranging methods for mobile robots (reference 1).

2.0 BACKGROUND

2.1 RANGING TECHNIQUES

2.1.1 Proximity

Proximity sensors are primarily used to determine the presence (as opposed to actual range) of objects moving near a sensing probe. The sensors were developed to gain position information in the close-in region (between a fraction of an inch and several feet), extending the sensing range beyond that afforded by direct-contact tactile or haptic sensors. Advances in electronic technology have improved the performance and reliability of these devices, thereby increasing the number of possible applications. Many installations which typically have used mechanical limit switches can now use proximity switches for their close-in sensing needs.

The reliability characteristics typically displayed by these instruments make them well suited for operation in harsh or otherwise adverse environments, while providing high speed response and long service lives. Instruments can be designed to withstand significant shock and vibration with some capable of handling forces over 30,000 Gs and pressures of nearly 20,000 psi (reference 2). Because of the sensor's ability to sense through nonferrous materials, proximity switches can be coated, potted, or otherwise sealed, permitting their operation in contaminated work areas and even submerged in fluids. In addition, proximity devices are valuable when detecting objects moving at high speed, when contact with an object may cause damage, or when differentiation between metal and nonmetal objects is required.

Proximity switches are classified into several major types related to the specific properties used to initiate a switching action. Permanent-magnet sensors are good for sensing ferrous metal objects over very short distances. They generally consist of a steel armature positioned between two permanent-magnetic fields which hold the armature in a constant position. When a ferrous object approaches, it diverts one of the fields, which allows the remaining field to become dominant. This field draws the armature to a contact, thereby closing a switch. This type of sensor has no applicability on a mobile robotic platform for purposes of object detection.

Continuing, induction-type proximity switches are applied to the detection of metal objects located at short range. Typical inductive sensors generate an oscillatory radio frequency (RF) field around a coil of wire. When a metal object enters the field, the effective inductance of the coil changes, resulting in an oscillator frequency shift that is converted into an output signal. Sensing range is approximately equal to the diameter of the sensing coil (reference 3). Inductive sensors in general have limited use for purposes of object detection, except in very application-specific instances. One such example involves a very large industrial manipulator which cleans the exterior hulls of ships in drydock (reference 4). Inductive sensors are used to sense the presence of the steel hull surface, controlling a servomechanism which keeps the manipulator under preloaded contact as it traverses the hull removing rust and marine growth.

Ultrasonic proximity sensors (not to be confused with ranging systems, which will be discussed later) are useful over longer distances (several feet) for detecting most objects, liquid, and solid. Most systems consist of two transducers, one to transmit, and the other to receive the return energy. When no object is present, the control circuitry indicates no output; when an object enters the acoustical field, energy is reflected back to the receiver. When the received signal reaches the preset threshold, the sensor output changes state, indicating detection.

Optical proximity sensors can be broken down into three basic groups: (1) break-beam, (2) reflective, and (3) diffuse. In the first of these categories, separate transmitting and receiving elements are physically located on either side of the region of interest. The transmitter emits a beam of light, often supplied by a light-emitting diode (LED), which is focused on the photosensitive receiver (figure 2a). Any object passing between the emitter and receiver breaks the beam, disrupting the circuit.

Figure 2b shows reflective optical proximity sensors which evolved from break-beam through the use of a mirror to reflect the transmitted energy back to a detector colocated with the transmitter. Corner-cube and cat's-eye retroreflectors quickly replaced the mirrors to cut down on critical alignment needs. In most cases, the object of interest is detected when it breaks the beam, although some applications call for placing the retroreflector on the object itself (i.e., beacons).

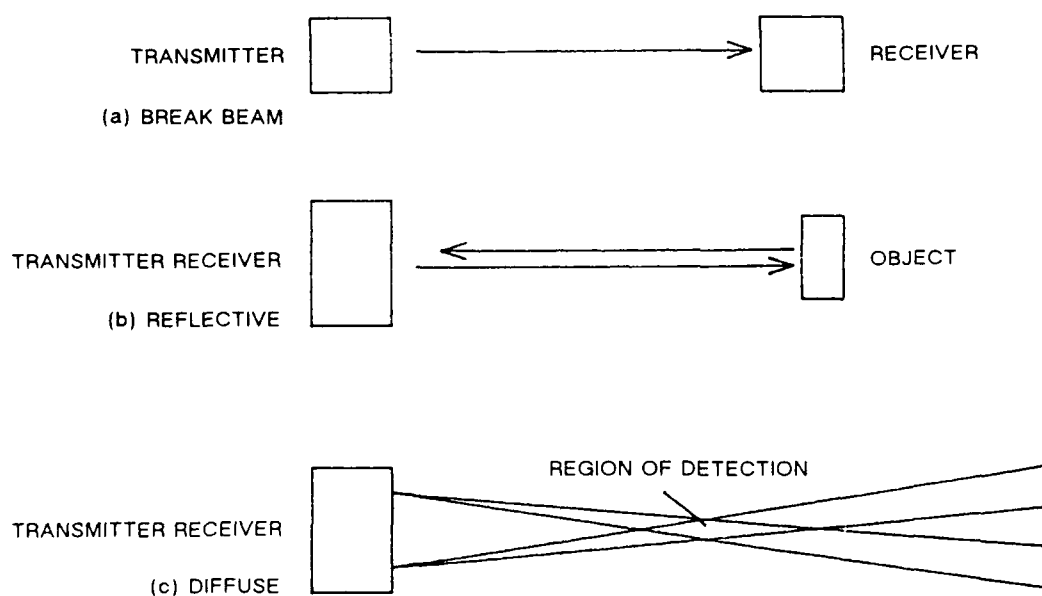


Figure 2. Optical proximity sensors can be broken into three categories: (a) break-beam, (b) reflective, and (c) diffuse. Figure 2c is a special case of the diffuse type, the convergent proximity sensor.

Sensors in the diffuse category operate in the same fashion as reflective, except that energy is reflected from the surface of the object of interest, as opposed to a cooperative target reflector. This is typically made possible through the use of modulated near-infrared energy to reduce the effects of ambient lighting, thus achieving the required signal-to-noise ratio for reliable operation. A subcategory of diffuse is the convergent optical proximity sensor, which employs a special geometry in the configuration of the transmitter with respect to the receiver to ensure more precise positioning information. Figure 2c shows, the optical axis of the transmitting LED is angled with respect to that of the detector, so that the two intersect only over a narrowly defined region. It is only at this specified distance from the device that a target can be in position to reflect energy back to the detector. Consequently, targets beyond this range are not detected. This feature decouples the proximity sensor from any dependence on the reflectivity of the target surface, and is useful where targets are not well displaced from background objects. Sensors of this type were used on ROBERT II (reference 5) to detect discontinuities in the floor surface, such as a descending stairway.

The final proximity classification to be discussed is the capacitive type, effective for short-range detection (a few inches) of most objects. Such sensors measure the electrical capacitance between a probe and its surrounding environment. As an object draws near, the changing geometry and/or dielectric characteristics within the sensing region cause the capacitance to change, affecting the current flow through the probe. The distance between the sensor and the target is inversely proportional to the probe current (reference 2). The use of this type of sensor for collision avoidance purposes is again extremely limited, and very application specific.

The performance specifications of proximity sensors depend on several factors. Effective range is a function of the physical characteristics (size, shape, and material) of the object to be detected, its speed and direction of motion, the design of the sensor probe, and the quality and quantity of energy it radiates or receives. Distance resolution is dependent upon object size, speed, and generally reduces with increased range. Finally, repeatability in detection is based on the size of the object to be detected, changes in ambient conditions, variations in reflectivity or other material characteristics of the target, and the stability of the electronic circuitry of the sensor.

2.1.2 Triangulation

This common ranging technique with ancient Greek and Egyptian origins has historically been used in ship navigation, surveying, and civil engineering applications. Triangulation presents a simple trigonometric method for calculating the distances and angles needed to determine object location. An important premise of plane trigonometry is that given the length of a side and two angles of a triangle, it is possible to determine the length of the other sides and the remaining angle. The basic Law of Sines can be rearranged as shown below to represent the length of side B as a function of side A , and the angles θ and ϕ :

$$B = A \sin \theta / \sin \alpha = A \sin \theta / \sin(\theta + \phi) .$$

In practical applications, length B would be the range to a desired object (figure 3).

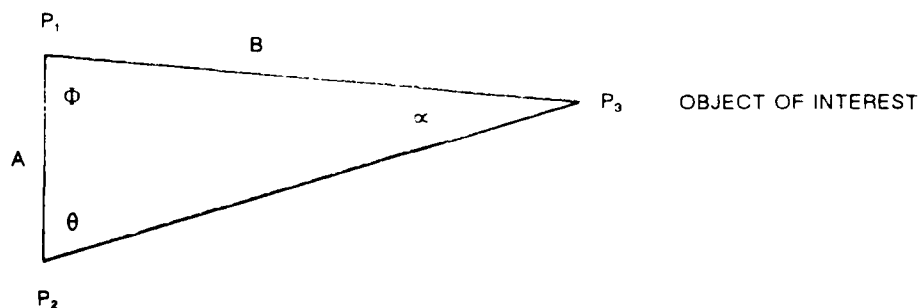


Figure 3. Triangulation ranging. Observed angles at P_1 and P_2 can be used in conjunction with known separation A to calculate the range to P_3 .

Ranging systems using triangulation for robot navigation and collision avoidance are classified as either passive or active. Passive stereoscopic ranging systems, which use only the ambient light of the scene to illuminate the target, position directional detectors such as TV cameras, solid state imaging arrays, or

photodetectors at positions corresponding to the locations P_1 and P_2 (figure 4). Both imaging sensors are focused on the same object point, P_3 , thereby forming an imaginary triangle. The distance between the detectors as well as their orientation angles can be measured and used to calculate the range to the object of interest.

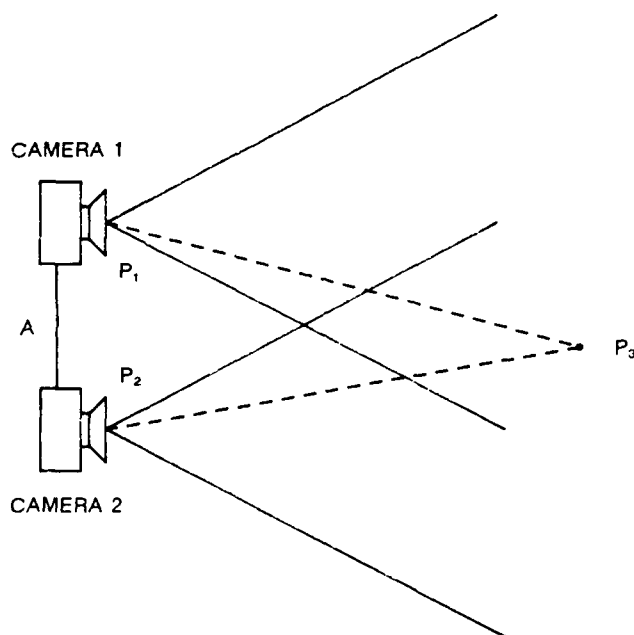


Figure 4. Stereoscopic ranging. Bearings to a common point of interest are measured using two cameras with known baseline separation A.

Active triangulation systems position at either point P_1 or P_2 a controlled light source, such as a laser, which is directed at the observed point, P_3 . A directional imaging sensor is placed at the remaining triangle vertex and is also aimed at P_3 . Illuminating energy from the source light will strike the target and be reflected, with a portion of the light falling on the detector, permitting range determination by the Law of Sines. In both passive and active systems, an array of range points can be determined by adjusting the incident angles of the detectors and/or the light source in a raster sequence. The resulting range map is a three-dimensional image of the environment in front of the sensor.

The performance characteristics of triangulation systems are to some extent dependent on whether the system is active or passive in nature. Passive triangulation systems require special ambient lighting conditions which must be artificially provided if the environment is too dark. Furthermore, these systems suffer from a correspondence problem resulting from the difficulty in matching points viewed by one image sensor with those viewed by the other. On the other hand, active triangulation techniques employing but a single detector do not require special ambient lighting, nor do they suffer from the correspondence problem. Active systems, however, encounter instances of no recorded strike because of specular reflectance or surface absorbance of the light.

Limiting factors common to all triangulation sensors include angular measurement inaccuracies and a "missing parts" problems. "Missing parts" refers to the occurrence where particular portions of a scene

can be observed by only one viewing location (P_1 or P_2). This situation arises because of the offset distance between the viewing locations, which can cause occlusion of the target. The design of triangulation systems must include a trade-off analysis of the offset; as this baseline measurement increases, the range accuracy increases but problems due to directional occlusion worsen.

2.1.2.1 Stereo Disparity. The first of the triangulation schemes to be discussed, stereo disparity, (also referred to as stereo vision, binocular vision, and stereopsis) is a passive ranging technique modeled after the depth measuring capabilities of the human eye. When a three-dimensional object is viewed from two locations on a plane normal to the direction of vision, the image when observed from one position will shift laterally when viewed from the other. This displacement of the image, known as disparity, is inversely proportional to the distance to the object. Practical ranging devices based on stereopsis use a pair of identical television cameras (or a single camera with the ability to move laterally) in order to generate the two disparity images. The cameras are typically aimed straight ahead, view approximately the same scene, and do not possess the capability to converge their center of vision on an observed point like the human eye can. This limitation makes placement of the cameras critical because stereo ranging can take place only in the region where the fields of view of the two camera positions overlap. A reference point corresponding to the center of vision is determined for both images, from which the displacement of the point of interest is measured. The difference in the displacements between the two images, the focal length of the cameras, and the distance between camera locations are used to calculate range.

There are four basic steps involved in this ranging process. First, a point in the image of one camera must be identified and located. Second, the same point must be located in the image of the other camera. Third, their positions must be measured with respect to a common reference and last, the distance to the point calculated from the disparity in the measurements (reference 6). On the surface this procedure appears straightforward; however, a major obstacle arises when attempting to locate the specified point in the second image, due to the same binocular disparity which is being used to determine range. The effort to match the two images of the point is called correspondence, and methods for minimizing this computationally expensive procedure are widely discussed in the literature (references 6, 7, 8, and 9).

Correspondence between images can occur only when the identified point lies in both views, giving rise to the "missing parts" problem where the range cannot be determined for a point seen in one view but otherwise occluded or not present in the other. To compensate, the baseline distance between the cameras can be shortened to increase the overlap area; however, measurement accuracy is decreased as separation diminishes. Matching is further complicated in regions where the intensity or color are uniform (reference 7). Additional factors affecting performance include the presence of shadows in only one scene and the variation in image characteristics resulting from viewing environmental lighting effects from different angles.

2.1.2.2 Active Triangulation. Ranging by active triangulation is a variation on the stereo disparity method of distance measurement. In place of one of the cameras is a laser (or LED) light source aimed at the surface of the object of interest. The remaining camera is offset from this source by a known distance, and configured to hold the illuminated spot within its field of view (figure 5).

From this image the range to the surface can be determined. For one- or two-dimensional array detectors such as vidicon or charge-coupled-device cameras, the range is typically determined from the known baseline distance and the position of the laser spot image on the array relative to some reference. For mechanically scanned single element detectors such as photodiodes or phototransistors, range is generally determined by measuring the rotational angles of the detector and/or source at the exact moment when the detector observes the illuminated spot. The trigonometric relationship between these angles and the baseline value are used to compute the distance.

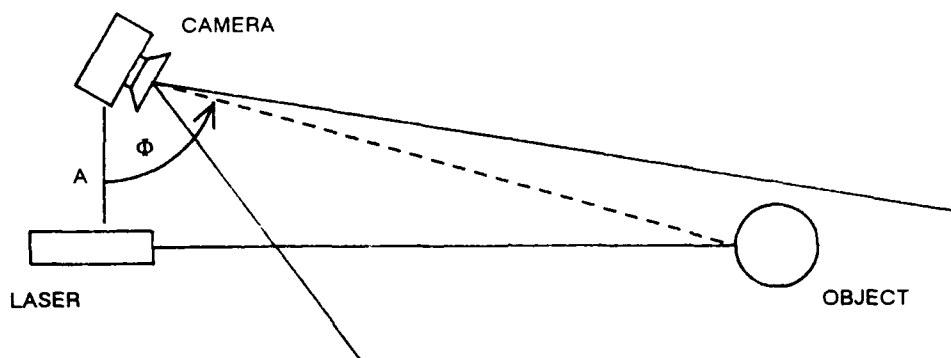


Figure 5. Laser Triangulation. Measured angle Φ decreases as the object moves closer to the camera and laser source.

To obtain three-dimensional information for an entire scene, laser triangulators can be scanned in both azimuth and elevation. In systems where the source and photodetector are fixed, the entire sensing configuration can be moved mechanically. In systems with movable optics, the mirrors, lenses, etc., are generally moved in synchronization. The major drawback to triangulation is the situation where points illuminated by laser cannot be seen by the camera and vice versa (missing parts) (reference 7). In contrast, the point source illumination of the image effectively eliminates the correspondence problem encountered in stereo disparity rangefinders.

2.1.2.3 Structured Light. Ranging systems which employ structured light are a further refined case of active triangulation ranging. An active light source projects a pattern of light (either a line, a series of spots, or a grid pattern) onto the object surface, while the camera observes the pattern from its offset vantage point. Range is determined by triangulation and manifests itself in the distortions caused in the pattern by variations in the depth of the scene. The use of these special lighting effects tends to reduce the computational complexity and improve the reliability of three-dimensional object analysis (reference 7). The technique is commonly used for rapid extraction of limited quantities of visual information for activities such as robot navigation, but also has applications to the tracking and acquisition of moving objects (reference 10).

The most common structured light ranging configuration entails projecting a line of light onto a scene while the other projects a grid pattern. The use of striped lighting was originally introduced by P. Will and K. Pennington of IBM Research Division Headquarters, Yorktown Heights, NY (reference 11). Their system created a plane of light by passing a collimated, incandescent source through a slit which projected a line across a scene viewable by an offset camera. (This line can also be formed by passing a laser beam through a cylindrical lens or by rapidly scanning the beam in one dimension.) Where the line intersects an object, the camera view will show displacements or kinks in the light stripe which are proportional to the depth of the scene. The result is in essence a two-dimensional contour line representing a narrow segment of the surface. The distance a point on the line in the image is from a reference point or line is representative of the range to the point. The proportionality constant between the light stripe displacement and depth is dependent on the length of the baseline between the source and the detector. Like any triangulation system, when the baseline separation increases, the accuracy of the sensor increases, but the "missing parts" problems worsen.

Three-dimensional range information for an entire scene can be obtained in relatively simple fashion through striped lighting techniques. By assembling a series of rapidly produced, closely spaced

two-dimensional contours, a three-dimensional description of a region within the camera field of view can be constructed. The third dimension is typically provided by scanning the laser plane across the scene. Compared to a single-point triangulation, striped lighting generally requires less time to scan over a surface, with fewer moving parts because of the need to scan only in one direction. Such systems have been able to construct images of a scene on the order of 200 times faster (reference 12). The inherent drawback to this concept is that range extraction is time consuming and difficult due to the necessity to store and analyze many frames.

A second structured light technique involves projecting a rectangular grid of high contrast light points or lines onto a surface. Variations in depth cause the grid pattern to distort, providing a means for range determination. The extent of the distortion is ascertained by comparing the displaced grid with the original projected patterns as follows: (1) identify the intersection point of the distorted grid image, (2) label these intersections according to the coordinate system established for the projected pattern, (3) compute the disparities between the intersection points and/or lines of the two grids, and (4) convert the displacements to range information (reference 13). The comparison process requires correspondence between points on the image and the original pattern which can be troublesome. However, by correlating the image grid points to the projected grid points, as in Step 2 above, this problem can be somewhat alleviated.

A critical design parameter is the thickness of the lines which make up the grid and their spacing. Excessively thin lines will break up in busy scenes, causing discontinuities which adversely affect the intersection points labeling process. Thicker lines will produce less observed grid distortion resulting in reduced range accuracy (reference 13). The sensor's intended domain of operation will determine the density of points required for adequate scene interpretation and resolution.

2.1.2.4 Known Target Size. A stadimeter is a hand-held nautical instrument used for optically measuring the distance to objects of known heights, between 50 and 200 feet, covering ranges from 200 to 10,000 yards. The stadimeter measures the angle subtended by the object, and converts it into range, which is read directly from a micrometer drum (reference 14).

The final variation on the triangulation ranging method to be discussed makes use of this same technique. Range is calculated through simple trigonometry; the known baseline, instead of being between two cameras (or a detector and a light source) on the robot, is now the target itself. The concept is illustrated in figure 6. The only limiting constraint (besides knowing the size of the target) is that the target must be normal to the optical axis of the sensor, which in the case of a passive system can be an ordinary CCD camera.

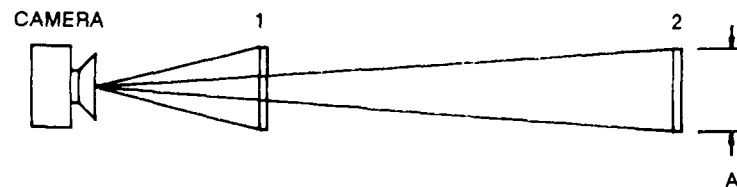


Figure 6. Known target size. The angle subtended by an object of known dimension is observed to increase as distance decreases in moving from position 2 to position 1, and can be used to calculate the unknown range.

The standard lens equation applies

$$\frac{1}{r} + \frac{1}{s} = \frac{1}{f}$$

where r = distance from lens to object viewed
 s = distance from lens to image plane
 f = focal length of the lens.

Now suppose the camera views an open doorway of known width A . If A is relatively small compared to the unknown distance r , then the range can be approximated by the formula (reference 15):

$$r = \frac{A f}{w}$$

where A = known width
 w = perceived width in image plane.

If the view angle for the object of interest is wide (i.e., A is not small with respect to r), then local geometric features should be examined (reference 15).

An active implementation of this ranging concept used on automated guided vehicles (AGVs) employs a scanning laser source which is mechanically coupled to a similarly rotating detector (section 3.1.10). A retroreflective target of known width is placed in a strategically located position so as to serve as a navigational aid. As the rotating laser scans across the retroreflector, energy is returned to the receiving detector. The length of the arc of rotation during which the detector senses reflected energy is directly related to the distance of the target; the closer the target, the longer the perceived arc.

2.1.3 Time of Flight. Another rangefinding technique originally used in surveying applications to accurately measure distances is time of flight (TOF), which refers to the time it takes for a pulse of energy to travel from its transmitter to an observed object then back to a receiver. The energy transmission typically originates from an ultrasonic, radio, or light source. The relevant parameters involved in range calculation, therefore, are the speed of sound (roughly 1 foot/millisecond), and the speed of light (1 foot/nanosecond). Time-of-flight systems measure the roundtrip time between an energy pulse emission and the return of the pulse echo resulting from its reflectance off an object. Using elementary physics, distance is determined by multiplying the velocity of the energy wave by the time required to travel the distance:

$$d = v t.$$

In this case the measured time is representative of traveling twice the distance and must, therefore, be reduced by half to result in actual range to the target.

The advantages of TOF systems arise from the direct nature of their active sensing. Transmissions are in a straight-line fashion from the transducer to the object. The returned signal follows essentially the same direct path back to the receiver, which is generally located coaxially with or in close proximity to the transmitter. In fact, it is possible for the transmitting and receiving transducers to be the same device. The absolute range to an observed point is directly available as output with no complicated analysis required, and the technique is not based on any assumptions concerning the planar properties of objects. The "missing parts" problem of triangulation does not arise because minimal or no offset distance between transducers is needed for the range calculation. Furthermore, time-of-flight sensors maintain

range accuracy as long as reliable signal detection is maintained, while triangulation schemes suffer diminishing accuracy as range increases.

The limitations of TOF systems are primarily related to the properties of the emitted energy, which vary across the spectrum. When light, sound, or radio waves strike an object, only a small portion of the original signal returns to be detected. The remaining energy reflects in scattered directions or is absorbed, depending on the characteristics of the object's surface and the angle of incidence (angle of approach) of the source transmission. The scattered signals can reflect from secondary objects as well and return to the detector at various times, resulting in false signals yielding questionable or otherwise noisy data. To compensate, repetitive measurements are averaged to bring the signal/noise response within acceptable levels, but at the expense of additional time required to determine a single range value.

Instances where no return signal is received can occur because of specular reflection by the object surface. (In specular reflection, the angle of incidence equals the angle of reflection). If the transmission source approach angle meets or exceeds a certain critical value, the reflected energy will be deflected outside of the sensing envelope of the receiver. This threshold angle is a function of the wavelength of the energy and the topographical characteristics of the target (reference 16).

Finally, the propagation speed of electromagnetic energy can place severe requirements on associated control and measurement circuitry. As an example, TOF sensors based on the speed of light require subnanosecond timing circuitry to measure distances with a resolution of about a foot (reference 3). This capability is expensive to realize and may not be cost effective for certain applications, particularly at close range where high accuracies are required.

Such laser-based time-of-flight ranging systems (also known as light or laser radar (LIDAR)) first appeared in work performed at the Jet Propulsion Laboratory in the 1970s (reference 17). Laser energy is emitted in a rapid sequence of short bursts aimed directly at the object being ranged. The time required for a given pulse to reflect off the object and return is measured, and used to calculate range based on the known speed of light. Ranging is direct and the calculations are not computationally difficult. Accuracies for sensors of this type approach a few centimeters over the range of 1 to 5 meters (reference 18).

2.1.4 Phase Modulation. Laser-based continuous wave (CW) ranging originated out of research performed at the Stanford Research Institute in the 1970s (reference 19). This well established method of distance measurement requires the transmission of a continuous wave of energy in contrast to the pulsed outputs used in direct measurement time of-flight systems, and involves a determination of the shift in phase of the signal as it returns from a reflecting object. An unbroken beam of modulated laser energy is directed towards the target; a portion of this wave is reflected by the object and returned to the detector along a direct path. This returned energy is compared to a simultaneously generated reference beam which has been split off from the original signal, and the relative phase shift between the two is measured. This phase shift is a function of the round trip distance the wave has traveled. Accuracies approach those achievable by pulsed laser TOF methods.

Further improved confidence in measured data can be obtained by integrating over many measurements for each observed location. This can be relatively time consuming, making it difficult to achieve real-time sensor systems. As with time-of-flight rangefinders, the paths of the source and the reflected beam are coaxial. This characteristic ensures that objects cannot cast shadows when illuminated by the energy source, preventing the "missing parts" problem.

Even greater measurement accuracy and overall range can be achieved when cooperative targets, such as retroreflectors, are attached to the objects of interest. These specular reflectors are geometrically configured such that incident light striking them will reflect back along a path parallel to the source beam, thereby increasing ranging capabilities because of the resulting increase in power density of the return signal.

The CW phase shift technique is the one most often found in electronic distance measuring instruments and automatic inspection systems; however, it possesses only a slight advantage over pulsed TOF rangefinding because the time measurement problem is replaced by the need for sophisticated phase measurement electronics (reference 18). Because of the limited information obtainable from a single range point, these sensors are often scanned in one or more directions by either electromechanical or acousto-optical mechanisms.

2.1.5 Frequency Modulation. An alternative to the phase modulation scheme discussed in Section 2.1.4 is frequency modulation (FM). Widely used in radar altimeter applications, FM radar involves the transmission of a continuous electromagnetic wave, modulated by a periodic triangular signal which varies the carrier frequency linearly above and below the mean frequency f_0 as shown in figure 7. The transmitter thus emits a signal that varies in frequency as a linear function of time:

$$f(t) = f_0 + a \cdot t.$$

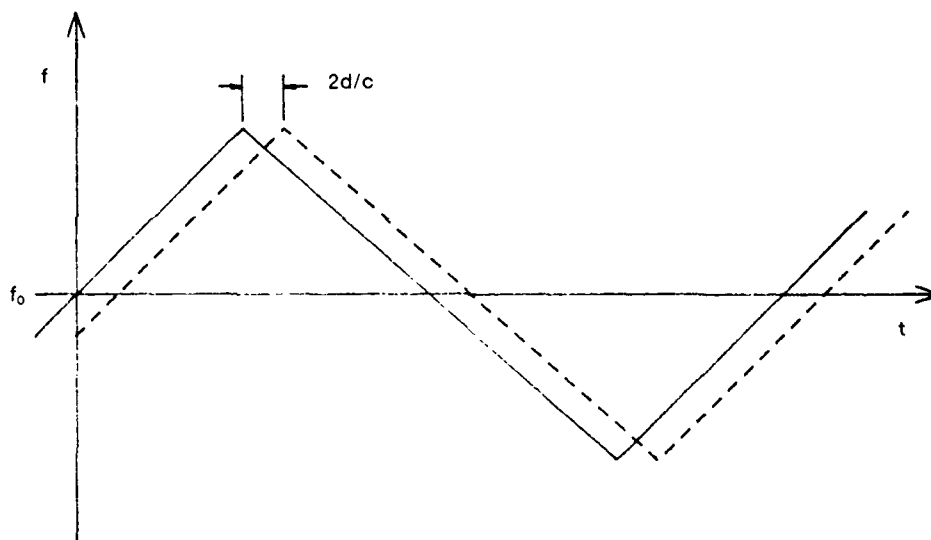


Figure 7. Frequency modulation. The reflected signal (dashed line) is displaced along the time axis by an amount proportional to the target range.

This signal is reflected from a target and arrives at the receiver at time $t + T$.

$$T = 2 \cdot d/c$$

where

T = round trip propagation time

d = distance to target

c = speed of light.

The received signal is compared with a reference signal taken directly from the transmitter. The received frequency curve will be displaced along the time axis relative to the reference frequency curve by

an amount equal to the time required for wave propagation to the target and back. (There might also be a displacement of the received waveform along the frequency axis, due to Doppler effect.) These two frequencies, when combined in the mixer, produce a beat frequency:

$$BF = f(t) - f(t + T) = a T.$$

This beat frequency can be measured, and used to calculate the distance to the object:

$$d = BF c / 2 a.$$

Distance measurement is as accurate as the linearity of the frequency variation over the counting interval.

Advances in wavelength control of laser diodes now permit this radar ranging technique to be used with lasers. The frequency or wavelength of a laser diode can be shifted by varying its temperature. Consider an example where the wavelength of an 850-nanometer laser diode is shifted by 0.05 nanometer in 4 microseconds. The corresponding frequency shift is 5.17 MHz/nanosecond; this laser beam, when reflected from a surface 1 meter away, would produce a beat frequency of 34.5 MHz. The linearity of the frequency shift controls the accuracy of the system. A frequency ramp linearity of 1 part in 1000 yields an accuracy of 1 millimeter.

The frequency modulation system has an advantage over the phase modulation technique in that a single distance measurement is not ambiguous. Phase modulation systems must perform two or more measurements at different modulation frequencies to be unambiguous. However, frequency modulation has several disadvantages associated with the requirements of coherence of the laser beam and the linearity and repeatability of the frequency ramp. It is not clear at this point in the development of the technology that the frequency modulation scheme is as simple as others presently available.

2.1.6 Interferometry. One of the most accurate and precise distance measuring techniques known, interferometric methods of measurement have existed for many years in laboratory scenarios which afforded the necessary controlled or otherwise structured environment (reference 20). In such nonturbulent atmospheric environments, laser interferometers can achieve fractional wavelength accuracies. Developments in optical technologies are now making possible applications of interferometry outside of the laboratory.

This ranging method is based on the resulting interference patterns which occur when two energy waves caused to travel different paths are compared. The primary energy source used to produce these waves is light. If the length of one of the optical paths is changed, the two beams will interact in such a way that clearly visible constructive and destructive interference fringes are produced. (Fringes are patterns or disturbances in the combined waveform which alternate between maximum and minimum intensity.) Figure 8 shows typical systems consist of a laser emitter, a series of beamsplitters and directional mirrors, and a fringe counter. (Beamsplitters operate by simultaneously reflecting and transmitting portions of a light beam.) Retroreflectors must be attached to objects which are to be tracked in order to provide a reliable return signal for the interferometer.

Initially, the transmission of a single coherent light source is split into a reference beam and an output beam. The reference beam is immediately directed into the fringe counter for future recombination with the reflected beam. The second beam exits the instrument and travels through the air to a retroreflector located on the object of interest. The returned signal is then sent directly back to the instrument by the retroreflector, where it is optically combined with the reference beam in the fringe counter. By counting the number of fringes passing a detector and knowing the wavelength of the light source in air, it is possible to calculate with extremely high accuracies the distance the retroreflector

(i.e., the object) has traveled along the line of the source beam. When the object moves a distance equal to half the light source wavelength, the movement and detection of one fringe will result (reference 21).

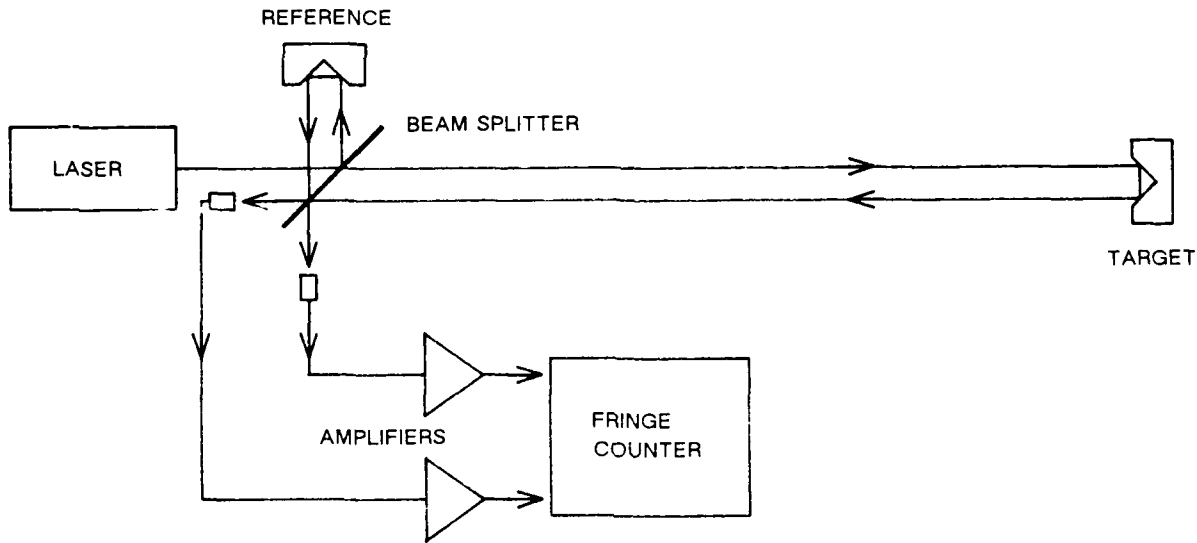


Figure 8. Interferometer block diagram. A retroreflector must be placed on the target of interest.

Interferometers do not measure absolute range, but the relative distance an object has moved from its previous location; therefore, the distance from the sensor to the target is not directly known. However, by initializing the retroreflector to a specified reference point it is possible to determine absolute distance to an object. All subsequent measurements will be distances from the reference point, provided the beam is never broken and the target momentarily lost.

In conventional interferometers, target displacement of 1 centimeter can result in the movement of approximately 10 million fringes past a detector capable of measuring changes on the order of one tenth (1/10) of a fringe (reference 21). Potential accuracies over a distance of 10 meters can approach 1/100,000,000; however, to achieve this, similar accuracy is required for the wavelength of the energy source. The maximum distance which can be measured by such instruments is therefore dependent on the coherent qualities of the source used. In theory, distances of hundreds of kilometers can be measured; however, this goal cannot be practically achieved using current technology (reference 21).

Important constraints on applying this ranging technique include (reference 20) the following constraints:

- a. Technique provides only relative distance measurement.
- b. Measurements are cumulative and therefore require continuous line-of-sight contact between the target and system.
- c. Measured distances lie along straight-line paths.
- d. A retroreflector must be installed on the object of interest.

Limitations of interferometers result from environmental factors as well as component characteristics. Air turbulence effectively reduces the practical range distance of such systems to 10 meters (reference 21). The turbulence causes large enough variations in the path lengths of the light beams so that no spatial coherence exists between the interfering beams; therefore, there are no fringes produced. Temperature changes and microphonic disturbances can cause fluctuations in components of the light source delivery system which alter the wavelength and intensity of the output (reference 21). The laser output must be stabilized to realize the full potential of interferometric measuring. Further functional limitations result from the nature of the light energy. Nonlaser light sources possess coherent lengths restricted to a few centimeters wavelength which consequently reduces the range of measurable distances.

The speed at which an interferometer can measure distances depends on the velocity of the object. The maximum detectable object velocity in turn is restricted by the maximum frequency response of the fringe counter detector. The use of interferometers in robotic applications was initially limited only to measurement of single-axis linear motion. Recent developments have expanded their applicability to three dimensional six degree-of-freedom (DOF) systems, known as "tracking" interferometers because the returning beam is also used by the system to track the lateral motion of retroreflective mirrors mounted on the object. Robotic tracking systems currently in existence are capable of precision tracking of manipulators performing nonrectilinear motions in six degrees of freedom (references 4, 20, and 22). While extremely precise, limiting factors of this method include the need for a continuous line of sight between the source and the retroreflectors, and the fact that the system is constrained to measuring only relative distance.

2.1.7 Swept Focus. The swept focus technique uses a modified video camera with a single lens of very short depth of field to produce an image in which only a narrow interval of range in object space is in focus at any given time. By means of a computer-controlled servo drive, this lens can be positioned with great accuracy over a series of positions in order to view different range "slices." (Some systems operate with a fixed-location lens, and vary the position of the detector element to achieve the same effect.) The distance between the lens and the image plane at the detector is related to the range at which the camera is focused (standard lens equation). Thus, if the lens is mechanically positioned to bring the desired object into focus, then the range to that object could be derived from the position of the lens.

An analog signal processor filters the video signal from the camera to obtain only the high frequency portion (figure 9). This represents information which changes rapidly across the scene, such as in-focus edges or textured material (the out-of focus portions of an image do not contribute to the high frequency information). This filtered signal is integrated during each video field time.

To perform ranging, the lens is successively positioned at hundreds of discrete, precalculated positions, reading, and storing the integrated high frequency data as it becomes available at each position before moving to the next. At the end of this process, the resultant profile of high-frequency response with range is processed to reduce noise effects, and then analyzed to determine the locations of all significant peaks. Each peak in high-frequency response represents the best-focus location of a target. The distance to each target can be found simply by reading from a look-up table the object range corresponding to the lens position where the peak occurred.

The speed of this type of sensor is currently limited by the standard video frame rate (60 frames/second). Ranging accuracy and the ability to separate targets closely spaced in range are limited by physical constraints of the lens. The greater the desired accuracy and resolution, the shorter the required depth of field, which can be achieved by using a lens of longer focal length or larger aperture. The tradeoffs involved are, respectively, reduced field of view and increased size and weight.

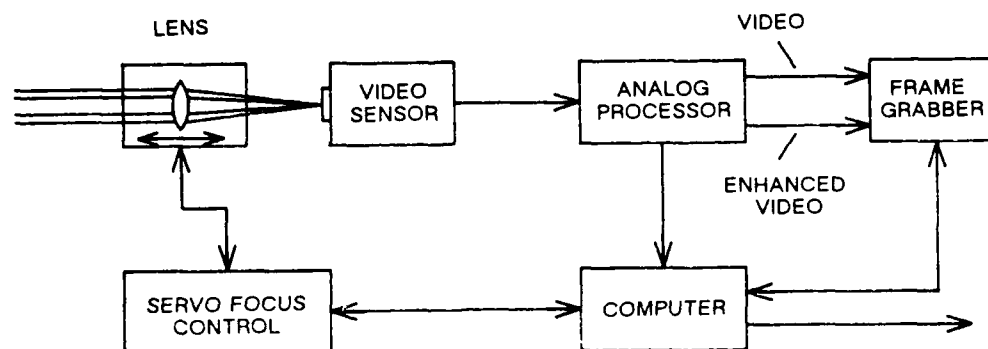


Figure 9. Block diagram of a passive swept-focus ranging system.
(Courtesy Associates and Ferren Corporation, Wainscott, NY)

Thus, through use of optical preprocessing, the swept focus technique provides the advantages of a visual sensor, while eliminating many of the major disadvantages of other visual techniques. For example, it is fast, has acceptable accuracy for most applications, will locate multiple targets at different ranges, is not computation intensive, does not suffer from the "missing parts" problem, and operates passively in ambient light. In addition, it is well suited to tasks such as tracking moving targets as well as three-dimensional image representation.

2.1.8 Return Signal Intensity. Ranging techniques involving return signal intensity determine the distance to an object based on the amplitude of energy (usually light) reflected from the object's surface. The inverse square law for emitted energy states that as the distance from a point source increases, the intensity of the source diminishes as a function of the square of the distance. If Lambertian object surfaces are assumed (Lambertian surfaces are ideal surfaces which in theory scatter reflected energy with equal probability in all directions (reference 7)), then this principle results in a computationally simple range calculation algorithm. This assumption eliminates from the calculation the problems of specular reflection due to surface topography. Requiring only a single detector, this ranging technique does not suffer from the "missing parts" problem common to triangulation systems. Unfortunately, however, objects in the real world are not ideally Lambertian in nature; in addition, the varying reflectivities of typical object surfaces preclude simple measurement of signal strength from being a reliable indicator of distance under most conditions.

One implementation of this ranging technique being developed at the Massachusetts Institute of Technology (MIT) Artificial Intelligence Lab involves using a pair of identical point source LEDs positioned a known distance apart, with their incident light focused on the target surface. The emitters are individually fired, and the returned energy from each is measured by a photodetector in a sequential manner. According to the inverse square law of emitted energy, if the power of both sources was the same, then the intensity of the return signal as sensed by the receiver should be the same, if the sources were colocated. However, in this case one of the emitters is closer to the scene than the other, resulting in a difference in the return signal intensity produced by the two sources. This measurable difference can be exploited to yield absolute range values, and the effects of varying surface reflectivities (which attenuate returned energy for both LEDs) cancel out.

Range to an object can be determined by relating the two intensities through a factor known as the brightness ratio, $B1/B2$. $B1$ is the return intensity produced by the more distant light source and $B2$ is the return intensity produced by the closer source. By the inverse square law

$$B1 / B2 = (L2 / L1)^2$$

where $L1$ = distance between farther emitter and object
 $L2$ = distance between closer emitter and object

realize that $L1$ is equal to $L2$ plus the distance d between the two light sources. Substituting this new value for $L1$ and evaluating the resulting quadratic produces an equation for the range, $L2$, as a function of d and the returned intensities, $B1$ and $B2$. Range can be calculated after measuring the intensities, since d is a known quantity set by the design of the sensor. Assumptions used in the above derivation are that all surfaces are Lambertian in nature, and that the width of observed objects is greater than or equal to the footprint of the incident illumination.

2.2 APPLICABLE TECHNOLOGIES

2.2.1 Acoustical. Acoustical energy has long been established as an effective sensing medium. As far back as 1918 with the development of SONAR (Sound Navigation and Ranging), high-frequency acoustic waves have been used to determine the position, velocity, and orientation of underwater objects. Though sensor systems for operation in air have been developed using acoustic transmissions in the audible frequency ranges, ultrasonic energy (sound waves above the limits of human hearing) has been the most widely applied. Ultrasonic transducers typically transmit at frequencies greater than 20,000 Hz, generated by both mechanical and electronic sources.

Acoustical ranging can be implemented using triangulation, time of flight, phase shift measurement, or a combination of these techniques. The direction and velocity of a moving object can also be determined by measuring the Doppler shift in frequency of the returned energy caused by objects moving toward or away from an observer. A minimum 10-Hz Doppler shift is necessary in order to determine an object's velocity with respect to its environment (reference 2). Typically, triangulation and time-of-flight methods transmit sound energy in pulses and are effective at longer distances for navigation and positioning, and at shorter distances for object detection. The phase shift ranging technique involving the transmission of a continuous sound wave is better suited for situations where a single dominant target is present.

The performance of ultrasonic ranging systems is significantly affected by environmental phenomenon and sensor design characteristics. Of primary concern is the attenuation of sound energy over distance. As an acoustical wave travels away from its source, its intensity decreases according to the inverse square law (also known as spherical divergence) and due to absorption of the sound by the air. (By the inverse square law, intensity of acoustic energy will drop 6 dB as the distance from the source is doubled (reference 23).) The absorption of sound energy varies with the humidity and dust content of the air as well as the frequency of the transmitted wave. Absorption can also occur at the reflecting surface and is a function of the topographical characteristics of the object being detected.

Consequently, the maximum detection range for an ultrasonic sensor is dependent on the emitted power and frequency of operation; the lower the frequency, the longer the range. For a 20-kHz transmission, the absorption factor in air is approximately 0.02 dB/foot, while a 40-kHz transmission loses between 0.06 and 0.09 dB/foot (reference 23). However, resolution of the system is dependent on the bandwidth of the transmitted energy, and greater bandwidths can be achieved at higher frequencies. Minimum ranging distance is also a function of bandwidth, and thus greater bandwidths and higher frequencies are required as the distance between the detector and target shortens.

Another parameter affected by the ambient properties of air is the velocity of sound. The principal factors involved are air temperature, which determines the interactivity of air molecules, and the wind direction and velocity, which have a push or delay effect on sound energy. Correction for wind effect errors must treat crosswind components as well as those which travel on a parallel path either with or against the sound. Crosswind effects are significant because they cause the beam center to be offset from its targeted direction, diminish the intensity of returned echos, and result in a slightly longer beam path due to deflection.

The speed of sound in air is proportional to the square root of temperature in degrees Rankine:

$$\text{Speed of Sound} = c = \sqrt{g k R T}$$

where g = gravitational constant
 k = ratio of specific heats
 R = gas constant
 T = temperature in degrees Rankine ($F + 460$).

For the temperature variations likely to be encountered in robotic ranging applications, this results in a significant effect even considering the short distances involved. Temperature variations over the span of 60 to 80 degrees Fahrenheit can produce a range error as large as 7.8 inches at a distance of 35 feet (reference 16). Fortunately, this situation can be easily remedied through the use of a correction factor based upon the actual ambient temperature, available from an external sensor mounted on the robot. The formula is simply

$$\text{Actual Range} = R_a = R_m \sqrt{T_a / T_c}$$

where R_m = measured range
 T_a = actual temperature (R)
 T_c = calibration temperature (R).

The possibility does still exist, however, for temperature gradients between the sensor and the target to introduce range errors, in that the correction factor is based on the actual temperature near the sensor only.

Still another factor to consider is the beam dispersion angle of the selected transducer. The width of the beam is determined by the transducer diameter and the operating frequency. The higher the frequency of the emitted energy, the narrower and more directional the beam, and hence the higher the angular resolution. Unfortunately, an increase in frequency also causes a corresponding increase in signal attenuation in air, and decreases the maximum range of the system. The beam dispersion angle is directly proportional to the transmission wavelength (reference 24), as shown below:

$$\theta = 1.22 \lambda / D$$

where θ is the desired dispersion angle
 λ is the acoustic wavelength
 D is the transducer diameter .

Best results are obtained when the beam centerline is maintained normal to the target surface. Figure 10 shows the angle of incidence varies from the perpendicular, however, note that the range actually being measured does not always correspond to that associated with the beam centerline. The beam is reflected first from that portion of the target that is closest to the sensor. For a 30-degree beam dispersion angle at

a distance of 15 feet from a flat target, with an angle of incidence of 70 degrees, the theoretical error could be as much as 10 inches. The actual line of measurement intersects the target surface at point *B* as opposed to point *A* (reference 16).

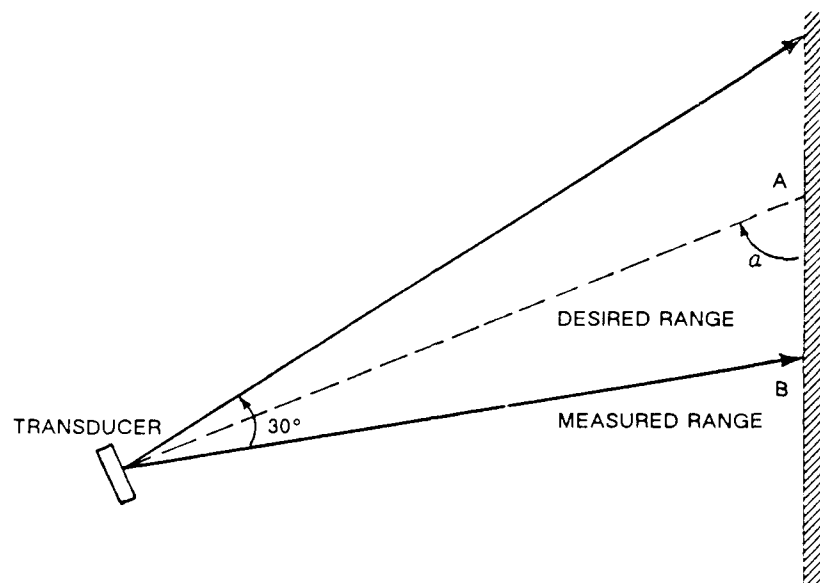


Figure 10. Ultrasonic ranging error due to beam divergence.

The width of the beam introduces an uncertainty in the perceived distance to an object from the sensor, but an even greater uncertainty in the angular resolution of the object's position. A very narrow vertical target such as a long wooden dowel maintained perpendicular to the floor would have associated with it a relatively large region of floor space that would essentially appear to the sensor to be obstructed. Worse yet, an opening such as a doorway may not be discernible at all to the robot when only 6 feet away, simply because at that distance the beam is wider than the door opening.

Finally, errors due to the topographical characteristics of the target surface must be taken into account. When the angle of incidence of the beam decreases below a certain critical angle, the reflected energy does not return to strike the transducer (figure 11). This angle occurs because most targets are specular in nature with respect to the relatively long wavelength (roughly 1/4 inch) of ultrasonic energy, as opposed to being diffuse. In the case of specular reflection, the angle of reflection is equal to the angle of incidence, whereas in diffuse reflection energy is scattered in various directions, caused by surface irregularities equal to or larger than the wavelength of incident radiation. The critical angle is thus a function of the operating frequency chosen, and topographical characteristics of the target. Offset from the normal will result either in a false echo as deflected energy returns to the detector over an elongated path, or no echo as the deflected beam attenuates.

In summary, ultrasonic sensors are a powerful and practical method of range determination for selected applications. Simple construction of the transducers makes them reliable and economical. The low-cost factor also makes design redundancy feasible, further improving system reliability and effectiveness. These points combined with the extensive use of ultrasonics in cameras, aids for the blind, health care, and other endeavors demonstrate the low technical risk involved in applying the technology where applicable.

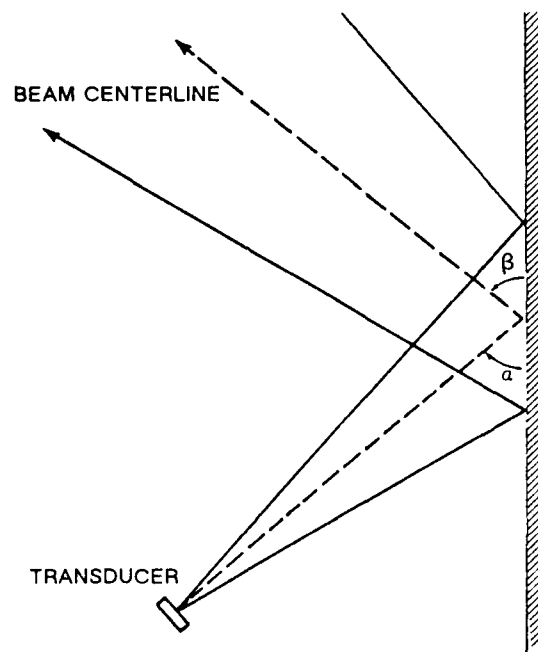


Figure 11. Ultrasonic ranging error due to specular reflection.

2.2.2 Optical. Active optical sources employed in rangefinding include broadband incandescent, narrowband LEDs, and coherent lasers. The actual source is chosen according to the following guidelines: (1) it must produce with sufficient intensity, (2) at the required wavelength (or within an appropriate spectrum), and (3) with the desired radiation pattern (reference 25). The design is optimized around these features to extract the necessary information from ambient noise and clutter with a comfortable signal-to-noise ratio.

Super luminescent diodes (SLDs) are a new development that can best be described as midway between the coherent laser diode and the more simplistic LED. The construction of all three of these devices is very similar; a forward-biased p-n junction leads to a recombination of holes and electrons with an accompanying emission of photon energy. An LED produces spontaneous emission in its active region, with a moderate spectrum about a central wavelength. Laser diodes, on the other hand, are physically configured such that emissions in the active region oscillate back and forth several times between the specially designed front and back facets, with the characteristic laser "gain" on each forward pass. This results in a primary wavelength or mode of operation, and what is termed a coherent output (reference 25).

LEDs have no such amplification mechanism; the output intensity simply increases with an increase in current density. Surface-emitting LEDs have a wide solid angle output beam, and the beam intensity is Lambertian. Edge-emitting LEDs have a waveguide mechanism built into their structure, which results in a narrow Gaussian intensity pattern (reference 25).

An SLD, on the other hand, is very much like an edge-emitting LED, but with a single pass gain feature similar to that of the laser. This results in an increased power output over a conventional LED, but as current density is increased, the device is unable to attain the threshold for multiple pass gain as does a laser diode (reference 25).

Most optical proximity detectors employ near-infrared LEDs operating between 800 and 900 nanometers. SLDs have only recently emerged in the rapidly expanding field of fiber-optic communications and optical disc technology, and thus do not yet appear in applications involving noncontact ranging, although it's only a matter of time.

At present, therefore, the majority of active optically based distance measuring devices employ laser sources; such systems are generally considered to be the quickest and most accurate way to obtain range information (reference 18). Lasers can be found in ranging equipment based on triangulation, time of flight (TOF), phase modulation, proximity, interferometry, and return signal intensity. This dynamic expansion in usage can be better understood by recognizing some of the inherent qualities of laser light (reference 18).

First of all, lasers produce a bright, intense output which is important for long-distance ranging, and for distinguishing the signal from the background. Secondly, by nature or through use of corrective optics, laser beams are narrow and collimated, with little or no divergence. This property allows the source to be highly directional or spatially selective, because an intense beam of energy can be concentrated on a small spot at long distances. Furthermore, lasers generally transmit light of a single wavelength (spectrally pure), and therefore are void of extraneous signals and noise. This quality can be exploited in rangefinders by placing narrowband optical filters, which match the wavelength of the beam, in front of the detector component. Filters of this type will reject the ambient light, resulting in an improved signal-to-noise ratio for the system.

Along with these advantages there also exist significant disadvantages which must be taken into account (reference 18). All laser-based systems represent a potential safety problem in that the intense and often invisible beam can be an eye hazard. Furthermore, gas lasers require high-voltage power supplies which present some danger of electrical shock, although this can be dealt with easily enough. Another liability is that performance is dependent on the presence of a highly accurate beam delivery system for pointing, tracking, and scanning functions. In addition, the wide dynamic range of the returning energy (between 80 and 100 dB) complicates the design of the detector electronics. Laser sources typically suffer from low overall power efficiency. Lasing materials are often unstable and possess short lifetimes, resulting in reliability problems. Finally, some laser-based ranging techniques require the use of retroreflective mirrors or prisms at observed points, effectively eliminating selective sensing.

It is important to note that lasers exist in a variety of types. The more well known are gas lasers like helium-neon (He-Ne) or the solid-state variety like neodymium: yttrium aluminum garnet (Nd:YAG). The recent advent of semiconductor-based laser diodes has had significant impact on the rangefinder instrument community (reference 18). Although they have reduced power output and poorer spectral quality relative to other lasers, they are compact, rugged, reliable, and efficient, with sufficient quality of performance for most sensing needs. An often used semiconductor laser of this type is the gallium arsenide (GaAs) laser diode, which transmits in the near-infrared region.

The use of energy from the optical portion of the spectrum minimizes the specular reflectance problems encountered with acoustics, with the exception of polished surfaces (reference 26). Glass, clear plastic, and other transparent substances with little or no reflectance properties can cause problems. In fact, one of the most significant problems in optical range measurement is due to the unknown reflectivity of observed targets. This plus the specific angle of incidence of the transmitted laser beam causes the reflected light energy to vary in amplitude and intensity, requiring detection capabilities over a wide dynamic range.

To be used with mobile robotic systems, an optical ranging system must function effectively under normal ambient lighting conditions, which makes the choice of light sources critical. Some systems use an incandescent source which is directed through a slit or patterned mask and projected onto the surface.

Others use laser beams which are mechanically or electronically scanned at high rates to create the desired illumination. The major criterion for selecting a light source is to be sure that its intensity peaks at a spectral frequency other than that of the ambient light (reference 27). The camera (or detector) should be outfitted with a matching narrowband filter to complement the source and improve detection. For example, ultraviolet light with a wavelength between 0.2 and 0.3 micron is effective outdoors because the atmospheric absorption of ozone blocks the transmission of sunlight energy less than 0.3 micron in length. However, an ultraviolet source of the required power density level would be hazardous in indoor environments (not eye safe). Contrast this with infrared light near 2.8 microns which is better suited to indoor activities because man-made objects tend to reflect infrared energy well. Infrared loses its usefulness outdoors due to the inherent radiation emitted by the natural terrain, roadways, and objects (reference 13). Ambient light effects can also be reduced by modulating the source signal over time, then demodulating the received energy at the camera end, which effectively subtracts off the constant illumination of the background.

2.2.3 Electromagnetic. Radar (Radio Detecting and Ranging) is the determination of the distance and bearing to an object and/or its speed relative to an observer calculated through the measurement of reflected electromagnetic waves. The properties of the received echoes are used to form a picture or determine certain information about the objects that cause the echoes. Common uses include the detection and location of commercial and military ships and aircraft, as well as weather forecasting. Specific advantages of radar sensing include the ability to "see" through smoke, dust, or haze-filled environments such as battlefields, a strong base of existing knowledge originating prior to World War II, and the ability to be made radiation hard. When combined with the technology of computerized signal processing, radar systems can produce astonishing accuracies in terms of target discrimination and range computation (reference 28). Radars are also effective at measuring the speed of moving objects by Doppler shift methods, wherein the magnitude of the frequency shift of an energy wave reflected off a mobile target is proportional to its relative velocity.

Ranging is accomplished by pulsed time-of-flight methods or continuous wave (CW) phase or frequency modulation. Pulsed energy systems can detect targets up to distances on the order of tens of miles, relying on the measurement of the round trip time of a propagating wave. The high speed of propagation of the emitted energy makes short distance measurements difficult for this type of system because the extremely sharp short-duration signals which must be generated and detected are expensive and complicated to realize. Continuous wave systems, on the other hand, are effective at shorter ranges because the phase shift measurements are not dependent on the wave velocity. Power consumption drops because lower transmitter intensity levels are needed for shorter distances.

The basic radar equation expresses the relationship between the signal power received at the antenna as a function of the antenna size and the emitted power of the system:

$$S = \left(\frac{P G}{4 \pi R^2} \right) \left(\frac{\sigma}{4 \pi R^2} \right) \left(\frac{G \lambda^2}{4 \pi} \right)$$

where

S	= signal power received
P	= transmitted power
G	= antenna gain
λ	= wavelength
σ	= radar cross section of target
R	= range to target

The quantity in the first parenthesis represents the power density in the incident wave at the target. The first two terms in parentheses together give the power density of the returning wave at the radar antenna, and the last factor is the cross section of the receiving antenna (reference 29).

A major consideration in the implementation of radar ranging capability is the configuration of the transmitting and receiving antenna. Systems employing a single antenna typically feature a large concave reflector with the detector or "feed" positioned at the focal point of the dish. This set-up is exactly analogous to an optical telescope at its prime focus. The principal advantage of this single unit arrangement is that the antenna will collect all the returned energy which falls upon it from a beam that is inversely proportional to the diameter of the reflector (reference 30). The relationship is expressed in the equation below:

$$\theta = 1.22 \lambda / d$$

where θ is the beamwidth
 λ is the wavelength
 d is the diameter of the reflector.

The disadvantages include the need to manipulate a large diameter antenna system when the application requires narrow beams, and the effects of vibration and wind which can necessitate a massive supporting structure.

Phased-array antenna configurations present an alternative arrangement which assembles into an array multiple small antennae separated by distances of a few wavelengths. The transmissions from each antenna diverge and overlap with neighboring transmissions in a constructive and destructive fashion based on their phase relationships. By properly adjusting the phases, the overall antenna can be tuned to a desired direction and intensity, as well as electronically scanned across the field of view. The small size of the individual transmitter-receivers reduces the problems due to wind effects; however, the resulting smaller coverage area decreases overall effectiveness. Also, the requirement for electronically variable phase control increases the system complexity.

2.2.3.1 Microwave Radar. The portion of the electromagnetic spectrum considered to be the useful frequency range for practical radar is between 3 and 100 GHz (reference 30). The primary electromagnetic source used in most modern conventional radar systems is microwave energy (reference 28). This form of radiation, with wavelengths falling between 1 millimeter and 1 meter, is extensively used for surveillance, tracking, and navigation applications. Microwaves are also used for short-range sensing needs such as tail warning radar and ground control radar for aircraft involving distances in the hundreds of feet. Other uses include level indicators, presence detectors, and obstacle avoidance radars, operating over ranges from a few feet to several yards. Equipment for the transmission, receiving, and processing of the waveform is widely available. Microwave systems have been in the experimental stage for quite some time but only came into their prime within the last decade or so with the advent of inexpensive, reliable solid state components as alternatives to the typically fragile, power consuming thermionic devices (reference 28).

Microwave energy is ideally suited for long-range military sensing because the resolution is sufficient, attenuation of the beams in the atmosphere is minimal, and low-mode guiding structures can be constructed. The relatively long microwave wavelengths provide radar systems with an "all weather" capability because they overcome the absorption and scattering effect of the air, weather, and other obscuring factors; however, they are susceptible to specular reflections at the target surface, requiring receivers and signal processors with wide dynamic ranges. Shorter wavelengths (i.e., higher frequencies) can be used to produce systems with high-angular resolution and small-aperture antennae. High angular resolution is possible at longer wavelengths, but the antenna size becomes very large. For these reasons, conventional radar systems operating in the microwave portion of the energy spectrum have less applicability to the high-resolution collision avoidance needs of a mobile robotic platform.

2.2.3.2 Millimeter Wave Radar. The rapidly evolving millimeter-wave technology involves that portion of the electromagnetic energy spectrum from wavelengths of about 500 micrometers to 1 centimeter.

Millimeter waves possess several properties which differ substantially from microwave radiation. First of all, the shorter wavelengths result in a narrow beamwidth radar, with relatively small-sized antenna apertures for a given bandwidth. Consequently, more information can be obtained about the nature of targets than at larger wavelengths because of reduced scattering of the reflected signal by objects. The overall physical size of the system is reduced, but the smaller apertures result in less collected energy, which limits the effective range of the system. Secondly, millimeter waves possess an extremely wide frequency bandwidth (the entire microwave frequency range could be encompassed by a single band of the millimeter wave region), which translates into greater resolution and sensitivity for radar applications, larger data transmission rates for communications, reduced interference between mutual users of the band, and improved security because of the large space in which to hide.

Relative to microwaves, millimeter waves display greater interaction with the environment. This attribute is good in that millimeter wave sensors can detect small particles and can carry on frequency selective interaction with gases; however, the resulting atmospheric attenuation limits the range and prevents operation of such devices in all weather conditions. Likely applications of this technology include remote environmental sensing, interference-free communications and radar, low-angle tracking radar, high resolution and imaging radar, spectroscopy (reference 31), and mobile platform collision avoidance.

In tracking radar systems the antenna gain is frequency dependent; therefore, for a given size antenna aperture, the wavelength should be small if the range is to be long, which favors millimeter wave sources. Furthermore, the narrow beamwidth of millimeter wave transmissions is highly immune to the ground reflection problems arising when following targets at low-elevation angles, making such radars highly effective at low-angle tracking. In imaging radar, the wide bandwidth of the millimeter wave region can sense the size and shape of an object with high resolution.

Although there are no current commercial sources of millimeter wave ranging devices, several contractors are involved in supplying such equipment to the military. While development costs may run as high as \$1 million, with lead times approaching a year or more, the indication is that individual transmitter, receiver, and antenna units may eventually cost as little as \$100 apiece, and fit into packages as small as an 8-inch cube (reference 30).

3.0 CANDIDATE SYSTEM

3.1 COMMERCIALY AVAILABLE

This section of the survey is composed largely of information submitted by the respective vendors, or taken directly from their product literature, and is understandably somewhat positive in tone.

3.1.1 Polaroid Ultrasonic Ranging Unit

The Polaroid ranging module is an active time-of-flight device developed for automatic camera focusing, and determines the range to target by measuring elapsed time between transmission and the detected echo. This system is the most widely found in the literature (references 3, 32, and 33) and is representative of the general characteristics of such ranging devices. A very thin metalized diaphragm mounted on a machined backplate forms a capacitive transducer (references 34 and 35). The system operates in the transceiver mode so that only a single transducer is necessary to acquire range data. Polaroid offers both the transducer and ranging module circuit board for only \$39 when purchased in quantities of ten. A rugged "environmental transducer" has been developed for applications which may be exposed to rain, heat, cold, salt spray, and vibration. A new, smaller diameter transducer has just recently been introduced, developed for the Polaroid Spectra camera.

The original Polaroid system functioned by transmitting a 1-millisecond-duration "chirp" consisting of four discrete frequencies transmitted back to back: 8 cycles at 60 kHz, 8 cycles at 56 kHz, 16 cycles at 52.5 kHz, and 24 cycles at 49.41 kHz. This technique was employed to increase the probability of signal reflection from the target, since certain surface characteristics could in fact absorb and cancel a single-frequency waveform, preventing detection. It should be recognized, however, that the 1-millisecond length of the "chirp" was a significant source of potential error, in that sound travels roughly 1100 feet per second at sea level, which equates to about 13 inches per millisecond. The uncertainty and hence error arises from the fact that it is not known which of the four frequencies making up the "chirp" actually returned to trigger the receiver, but timing the echo always began at the start of the "chirp" (reference 16).

For the initial application of automatic camera focusing, designers were more concerned about missing a target altogether due to surface absorption of the acoustical energy; the depth of field of the camera optics would compensate for any small range errors that might be introduced. In actual practice, such errors rarely showed up, indicative of the fact that the theoretical absorption problem had been somewhat overstated. In fact, Polaroid has subsequently developed an improved version of the ranging module circuitboard, the SN28827, which greatly reduces the parts count and power consumption and simplifies computer interface requirements. This second-generation board transmits only a single frequency at 49.1 kHz.

The range of the Polaroid system runs from about 1 foot out to 35 feet, with a beam dispersion angle of approximately 30 degrees. The typical operating sequence is as follows:

- a. The control circuitry fires the transducer and waits for indication that transmission has begun.
- b. The receiver is blanked for 1.6 millisecond to prevent false detection due to transmit signal ringing.
- c. The received signals are amplified with increased gain over time to compensate for the decrease in sound intensity over distance.

- d. The first echo to exceed a threshold value is captured, its time is recorded, and the distance is calculated.
- e. The receiver will listen for 62.5 millisecond then prepare for subsequent transmissions.

3.1.2 Sonatech Underwater Collision Avoidance System

Sonatech's terrain and obstacle avoidance sonar (TOAS) has been designed specifically to meet the needs of high-speed autonomous underwater vehicles (AUVs). TOAS is a lightweight, low-power, high-information rate, multibeam sonar providing bearing, range, and target size to the vehicle's processors (reference 36). Through these inputs, the vehicle is able to perform effective avoidance or homing maneuvers. The very nature of autonomous underwater operation greatly magnifies the performance requirements of collision avoidance sensors and simultaneously restricts their size, weight, and power budgets. The system must be optimized to present a realistic, undistorted field of view, the information rate must be high, and at the same time, the amount of data to be processed must be minimized.

Figure 12 shows a TOAS, mounted in the nose of a vehicle, which covers a forward projected volume 55 by 33 degrees encompassing the vehicle's near field course. This forward-looking coverage is divided into 15 cells each 11 by 11 degrees; range extends from the vehicle forward to beyond 1,000 feet, with a resolution of 0.8 meters. Each cell is created by an individual acoustic array found within the TOAS hydrophone. This acoustically sensed volume is insonified using a processor-controlled forward-looking projector whose source level is 196 dB re μ Pa. The projector can transmit from 1 to 3 times per second with a variable transmit pulse width, ranging from 1 to 10 milliseconds. The 86-watt source level is also programmable over a 30-dB range. Such control gives the system the ability to rapidly collect many acoustic returns from weak targets, thus reducing the target ambiguity.

Each sensed cell within the TOAS field of view is made up a single preformed conical beam having an 11-degree solid angle. Side lobes on these beams are down 30 dB, allowing the TOAS system to maintain strict 11-degree resolution free from side lobe interference. The 3-by 5-cell matrix results from a 15-beam contiguous array made up of three curved arrays. Each of these arrays receives five acoustically adjacent 11-degree beams; three arrays are stacked resulting in a 33-by 55-degree pattern. Acoustic returns in each cell are conditioned through processor controlled step and time varied gain amplification circuits, providing up to 90 dB of gain, for a maximum system dynamic range of 118 dB. Final signal conditioning on each of the 15 channels consist of envelope detection with analog output.

Conventional mechanically scanned narrow beam sonars sweep a wide vertical beam (25 to 50 degrees) which has a narrow horizontal beam (1.4 to 2 degrees) to provide azimuthal resolution. These are plagued with slow scan rates and generally no target height information. Typical scans of a 55-degree sector can take minutes. These features adversely affect the usefulness of mechanically scanned systems as AUV collision avoidance sensors in three ways: first, each scan results in only one acoustic return from all small targets (including minimum resolution targets), which often result in ambiguous or false signals. Second, during the sweep vehicle position changes, invalidating the recorded range and bearing to the obstacle. This can lead to disorientation, particularly when there is strong cross current. Last, the horizontal scan alone cannot resolve the vertical height of the target. Without altitude or height information, it is harder for the system to make the appropriate decisions to pass clear of the obstruction.

Mechanically scanned CTFM sonars (see section 2.1.5) are also plagued with the same reliability problems associated with other mechanically scanned devices, though they do increase information rates to well above those seen in narrow-beam mechanically scanned sonars. To make this improvement, CTFM converts range (time) to the frequency domain by transmitting a continuous sawtooth frequency slide. Returned reflected acoustic waves are converted to electrical signals at the scanning transducers. These are mixed with the sawtooth slide and the frequency difference processed giving the range to the target. The bearing to the target results from readings of the transducer position with resolution, a function of horizontal beamwidth (normally near 2 degrees).



Figure 12. Forward looking coverage of TOAS system is divided into 15 cells.
(Courtesy Sonatech, Inc.)

Selected Specifications

General

Range	1000 feet
Resolution	30 inches (0.8 meter)
Operating Frequency	200 kHz \pm 200 Hz
Number of Beams	15 (5 per receiving module)
Depth	1500 feet (can be increased)
Temperature Range	-2 degrees to 70 degrees C
Power Consumption	25 watts (in 15 beam version)

Sound Head (Transmitter)

Size	5-inches diameter, 6-inches long
Type	Anodized aluminum
Beam Width	60 \pm 5 degrees horizontal, 50 \pm 10 degrees vertical
Output Power Density	8 watts/centimeter ² (well below cavitation)

Receiving Hydrophone

Size	5 x 6 x 3-inch rectangle
Type	Cylindrical multi-element array
Beamwidth	Preformed: 11 degrees vertical by 11 degrees horizontal by 11 degrees spacing (@ -3 dB points)
Sensitivity	-176 dBV/1 μ Pa (each beam)
Power Consumption	0.2 watts per 5 beam module

Point of Contact

Jon Warner
Sonatech, Inc.
897 Ward Drive
Santa Barbara, California 93111-2920
(805) 683-1431

3.1.3 Banner Near-Infrared Proximity Sensor

Banner Engineering offers a full line of modular near-infrared proximity sensors of the break-beam, reflective, and diffuse type (see section 2.1.1). Effective ranges vary from a few inches out to 6 or 7 feet; applications include floor sensing and collision avoidance (references 5 and 16). Full details and application notes are provided in their catalog (reference 37).

3.1.4 Pentax Near-Infrared Autofocus Sensor

The Pentax Corporation has developed an autofocusing mechanism used in its Sport 35 camera which is illustrative of the potential for application of such systems to the close-in ranging needs of mobile robotic platforms. The Focus Control Module (FCM-A) is an active distance-measuring device which determines range by simple triangulation. The autofocusing unit consists of a near-infrared light-emitting diode (LED) with collimating optics, a single silicon photodiode detector offset from the light source, a position-determining scanning plate which traverses across the detector's surface, and the associated circuitry (figure 13).

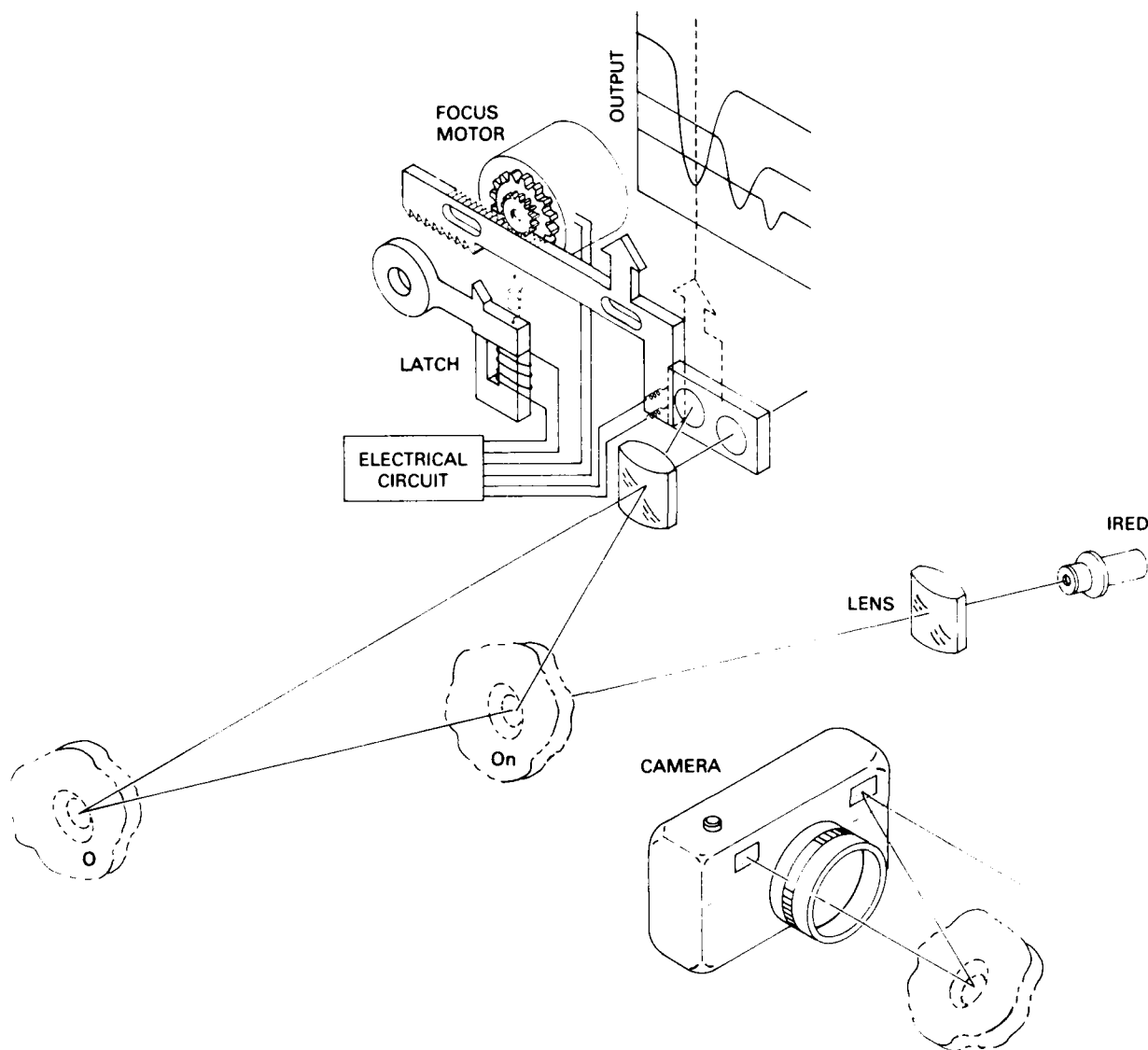


Figure 13. Illustration of FCM-A autofocus principle. (Courtesy Pentax Corporation)

The LED emits a continuous wave source beam through its focusing lens along the optical axis to the target. A portion of the energy is reflected back to the sensor where the beam illuminates a spot on the surface of the photodiode. The output of the detector then normalizes to the photo-electric current produced by the light, whereupon the scanning plate is electromechanically moved across the SPD in discrete increments or steps until it blocks the path of the reflected beam. This prevents the reflected light spot from reaching the photodiode, and effectively drops the output current to zero. At that moment, the near-infrared source is converted to pulsed energy in order to limit the effect of ambient light. The scanning plate continues across the detector until the spot strikes the surface again and the current rises back to normal. The current profile across the photodiode is analyzed by the detection circuitry; the point where the current drops to its maximum negative value (minus peak detection) is the centroid of the spot.

The lateral location of the spot is representative of the sensor-to-object range. Figure 13 shows distant objects, the return beam travels along a path and the spot falls on the far right side of the detector. As an

object moves closer, the spot moves across the detector from right to left. The minimum measurable distance is obtained when the spot falls on the far left side of the photodiode.

The FCM-A provides a viable range measurement capability for camera autofocus, where range resolution is not critical. It would be possible to modify the sensor for effective application to mobile robot collision avoidance needs by increasing the baseline separation between the source and the detector, increasing the power of the laser source and by increasing the sensitivity of the detection circuitry. In 1983, the sensor was commercially available as a shutterblock/autofocusing unit assembly under Part Number 24600-0-EO for \$53.77.

Selected Specifications

Ranging Technique	Active triangulation
Maximum Range	4 meters
Minimum Range	0.75 meter
Range Increment	8 steps
Range Accuracy	± 1 step
Measuring Time	70 milliseconds
Light Source	Near-infrared LED transmitting at 4 kHz
Beam Projection Angle	1 degree, 20 minutes
Power Requirements	3.5 VDC at 50 milliamps (250 milliamps peak)
Operating Temperature	-20 to +50 degrees Centigrade

Point of Contact

Pentax Corporation
35 Inverness Drive East
Englewood, Colorado 80112
(303) 773-1101

3.1.5 Honeywell HVS-300 Three Zone Distance Sensor

Honeywell Visitrionics of Englewood, Colorado, has developed a noncontact, near-infrared proximity gage which employs a triangulation ranging technique to determine relative distance as well as the presence or absence of an object. The HVS-300 Three Zone Distance Sensor is capable of indicating whether a surface within its field of view is close to the sensor, at an intermediate distance, far from the sensor, or out of range. Conventional diffuse proximity detectors based on return signal intensity display high repeatability only when target surface reflectivity is maintained constant. The HVS is capable of much higher range accuracy under varying conditions of reflectivity and ambient lighting due to the use of the triangulation ranging scheme (reference 38). Intended applications include low-cost inspection for zero-defect manufacturing systems, small part position detection, conveyor system parts location, tool position indicators, robot arm position indicators, hole depth inspection, and fill level detectors.

The HVS-300 proximity sensor consists of a pair of near-infrared LED sources, a dual-element silicon photodetector, directional optics, and control logic circuitry. The IR emitters transmit coded light signals at differing angles of incidence through one side of a directional lens and into the environment. If emitted energy strikes an object, a portion of the transmission is returned through the other side of the lens and focused onto the detector assembly.

The detector employs two photodiode elements placed side by side, separated by a narrow gap. Depending on the range to the reflective surface, a returning reflection will either fall exclusively on one photodetector (which indicates that the reflecting surface is close to the sensor), or the other (which indicates that the surface is far from the sensor), or equally on both (which means the object is on the

boundary between these two regions). Changing the incidence angle changes the distance this boundary lies from the sensor.

With two transmissions projected onto the scene at different angles of incidence, two such boundaries are created. The first distinguishes between the near and intermediate regions, while the second distinguishes between the intermediate and far regions (figure 14). Because both transmissions use the same detector, the sources must be coded so that the control electronics can distinguish between them and determine which regions they represent.

System response is on the order of 10 milliseconds. The HVS-300 can be adjusted to operate between the ranges of 2.5 inches and 30 inches. Adjustment is manual, and fixed prior to operation. At maximum range the system switch point repeatability approaches 1 percent but can be better than 0.05 percent at a range of 6 inches. The size of the intermediate region is limited and is determined by the emitter which sets the closest boundary. The irradiation pattern of the light source is 1.5 by 0.5 degrees, which forms an oblong spot on the target of interest. Spot size is dependent on object range. Sensor output is in the form of a logic signal representing the range states (near, OK, far, or out of range).

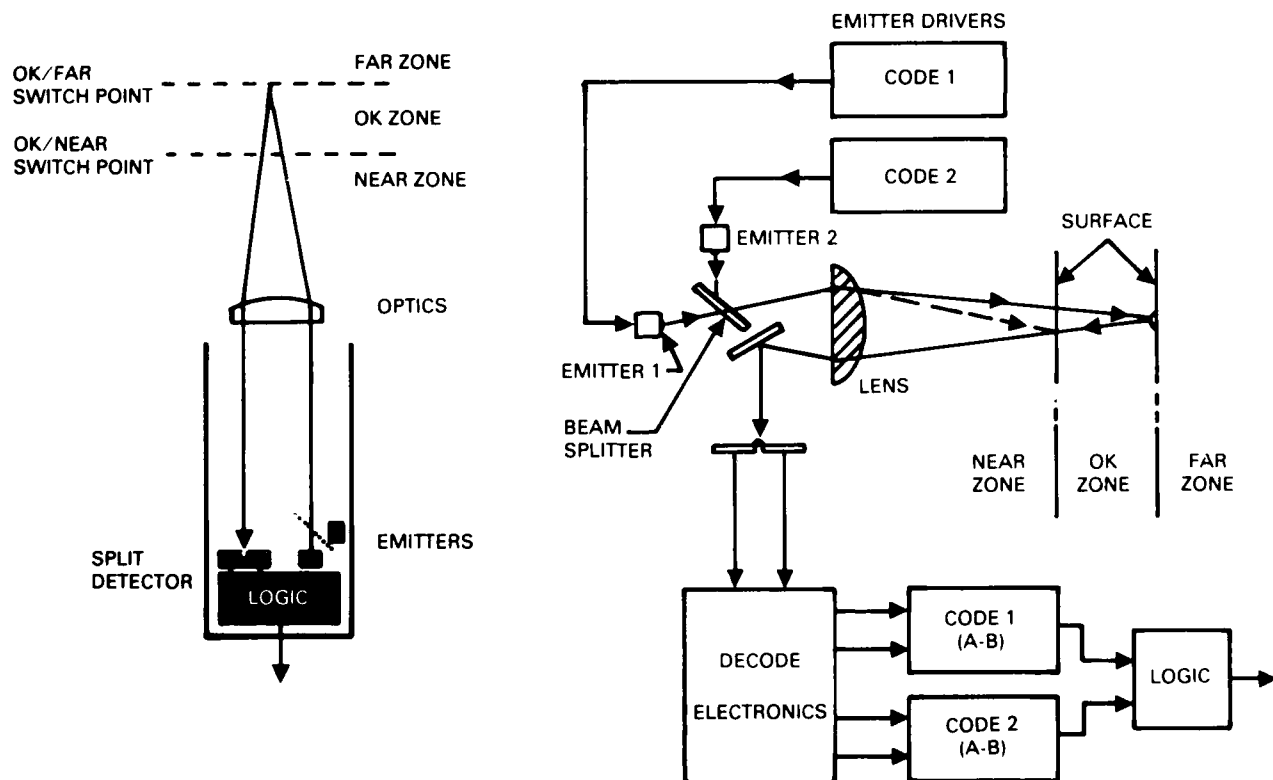


Figure 14. The HVS 300 distance sensor gauge uses dual active near-infrared emitters to detect if an object is in the adjustable OK zone. (Courtesy Honeywell Corporation)

In general, the HVS-300 is insensitive to changes in surface texture or color and is unaffected by ambient light conditions. Such a system would find application as a close-in proximity sensor for the collision avoidance needs of an indoor mobile robot, where speed of advance would be limited and in keeping with the sensor's maximum range of 30 inches. The three discrete range zones would give a relative feel for the distance to a threatening object, allowing for more intelligent evasive maneuvering.

Point of Contact

Honeywell Visitronics
P.O. Box 5077
Englewood, Colorado 80155
(303) 850-5050

3.1.6 Honeywell Visitronic Autofocus System

The first practical autofocus system for lens-shutter cameras was developed by the Honeywell Visitronic Group in 1976. The system employs a variation of the stereoscopic ranging technique, nicely optimized for low-cost implementation through the development of a special purpose integrated circuit for autocorrelation. Two five-element photosensitive arrays are located at each end of the Visitronic IC, which measures about 0.1 by 0.25 inch in size (reference 39). Figure 15 shows a pair of mirrors reflect the incoming light from two viewing windows at either end of the camera housing onto these arrays. One of these images remains fixed while the other is scanned across its respective array through the mechanical rotation of the associated mirror. The angular orientation of the moving mirror at the precise instant that the IC indicates the two images are matched is directly related to the range of the subject, and used to position the camera lens.

The photocurrents from corresponding elements in each array are passed through a string of diodes on the IC and thus converted to voltages proportional to the log of the current. The resulting pair of voltages is then fed to a differential amplifier, which produces a difference signal proportional to the ratio of the two light intensities as seen by the respective detectors (reference 39). For four of the five array pairs, the absolute values of these difference signals are summed and the result subtracted from a reference voltage to yield the correlation signal. The better the scene match, the lower the differential signal for each array pair, the higher the correlation signal.

The peak value of the correlation signal corresponds to the best scene match. An operational amplifier on the IC makes a continuous comparison between the correlation output and the previous highest value, which is stored in a capacitor. The output from this comparator is high as long as the correlation signal is lower than the previously stored peak value. Figure 16 shows the last low-to-high transition represents the mirror angle corresponding to the highest peak.

The output of the autofocus system was used to position the camera lens for best focus. A potentiometer on the moving mirror produced a voltage which varied as a linear function of mirror position. The output of this potentiometer was sampled and stored when the IC indicates the peak correlation signal was present. A similar potentiometer coupled to the camera lens positioning mechanism was used to stop the lens travel when its output matched the stored voltage signifying mirror position at best focus.

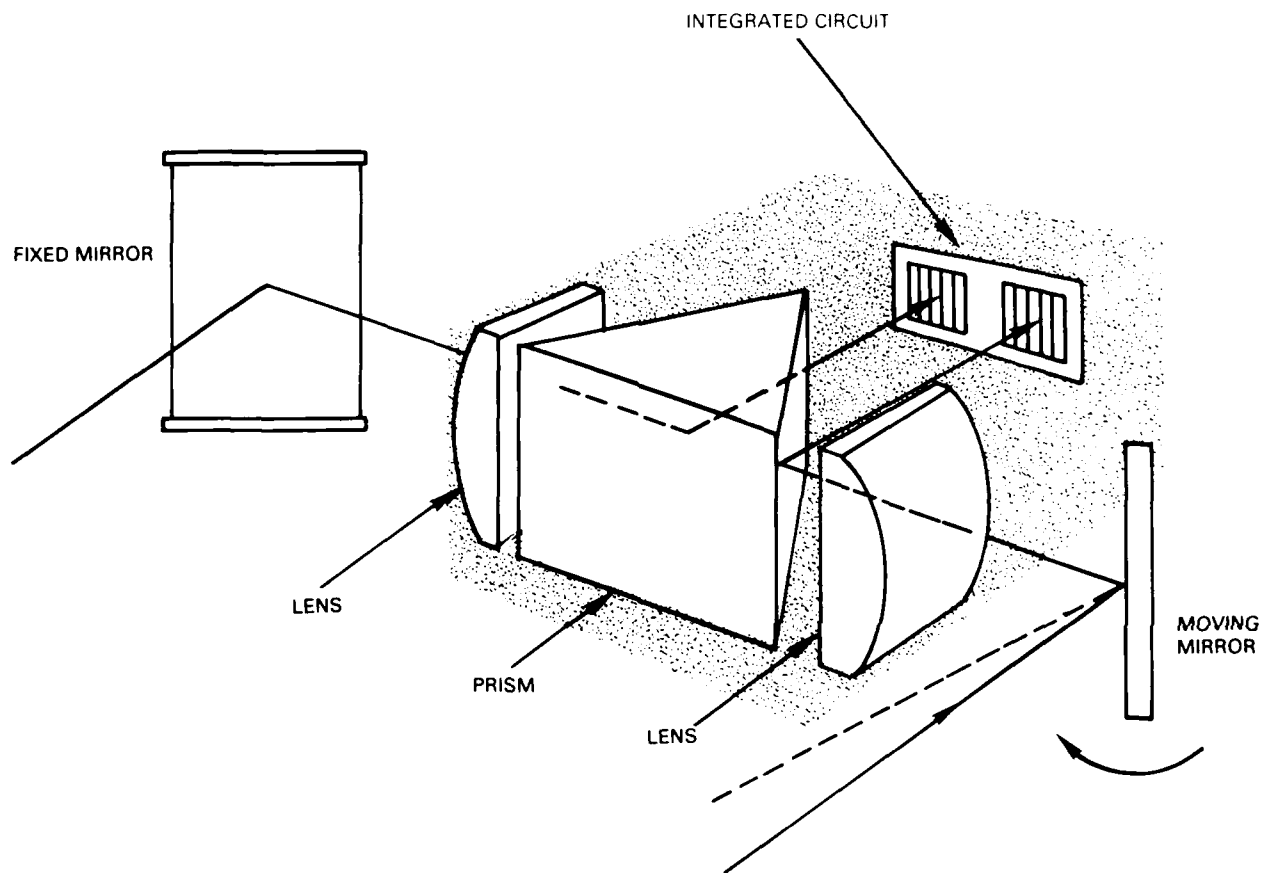


Figure 15. Illustration of the Visitronic Autofocus System developed in 1976.
(Courtesy Honeywell Corporation)

Like the active triangulation scheme employed in the Pentax Autofocusing System discussed in section 3.1.4, the passive Honeywell System was developed for a short-range application where accuracy was not critical. The system clearly illustrates, however, the feasibility of a small, low-cost, low-power passive ranging system, and suggests improved results more suitable to the needs of a mobile robot could be readily achievable, as discussed in section 3.1.7.

Point of Contact

Honeywell Visitronics
P.O. Box 5077
Englewood, Colorado 80155
(303) 850-5050

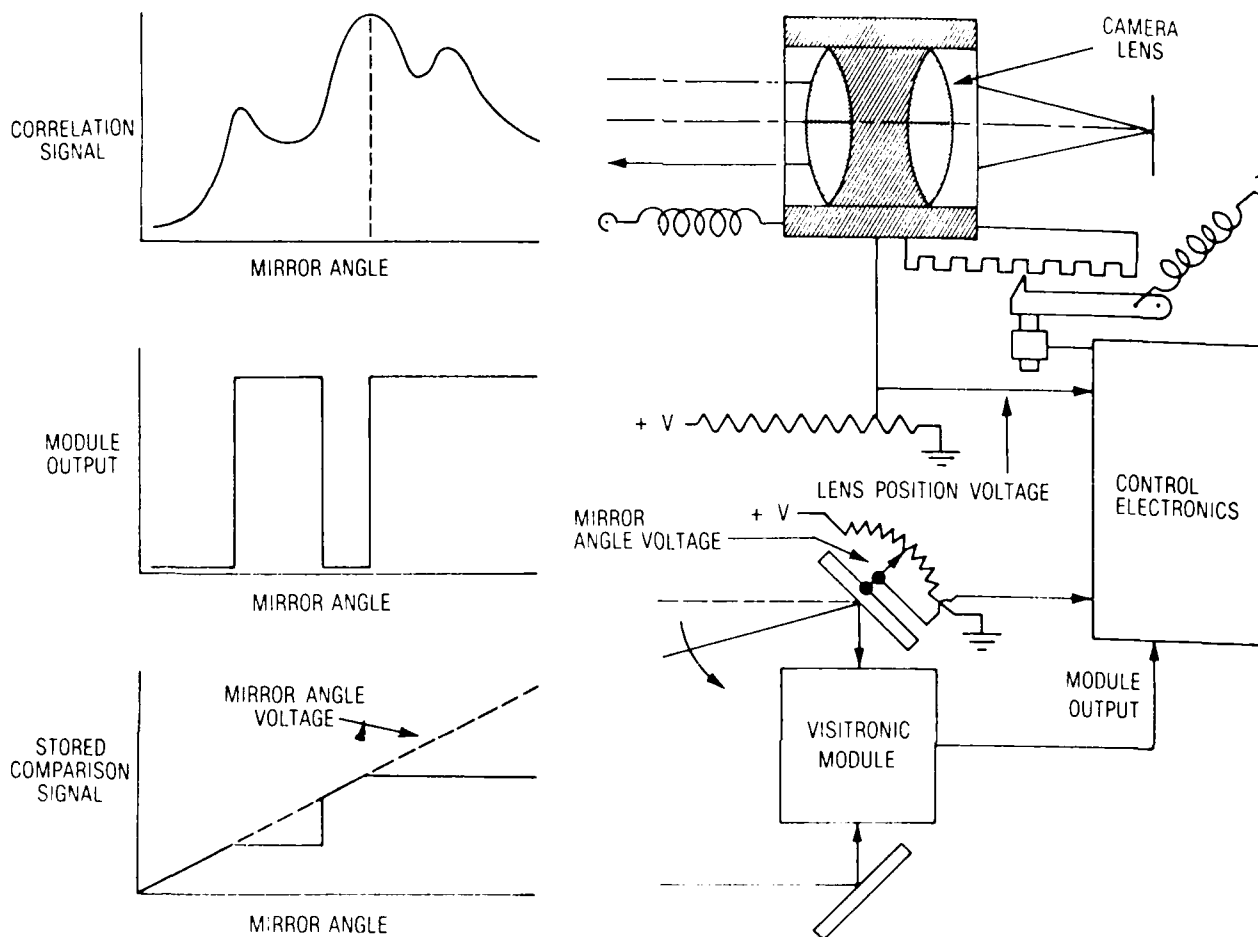


Figure 16. Schematic diagram of Visitronic Autofocus System.
(Courtesy of Honeywell Corporation)

3.1.7 Honeywell Through-the-Camera Lens (TCL) Autofocus System

The Honeywell TCL Autofocus System is a second-generation refinement of the Visitronic System, comparing the signatures of light passing through two different sectors of the camera lens, as opposed to two separate viewing windows. Instead of five, there are 24 pairs of detectors arranged in a single array about 5 millimeters long (two complete arrays are provided to accommodate lenses with different aperture sizes) (reference 39).

Light from any given point in the field of view of a camera passes through all sectors of the camera lens, and subsequently arrives at the image plane from many different angles. If the lens is in focus, these components all converge again to a single point in the image plane. If the lens is not in focus, these components are displaced from one another, and the image becomes fuzzy.

Similarly, light from every point in the scene of interest passes through each sector of the lens. Thus, each sector of the lens will contribute a recognizable signature of light to the image plane, in keeping with

the image viewed. (Early pinhole cameras made use of this principle; essentially there was only one sector, and so there was only one image, which was always in focus.) Practically speaking, these signatures are identical and if the lens is in focus, they will be superimposed. As the lens moves out of focus, the signatures will be displaced laterally, and the image blurs.

Figure 17 shows the Honeywell TCL System detects this displacement for two specific sectors (A and B) located at opposite sides of the lens. Light from these two sectors falls upon a series of 24 microlenses mounted on the surface of the integrated circuit, and in the camera image plane. An array of sensors is positioned within the IC a specified distance behind the image plane in such a fashion that light incident upon the row of microlenses and their associated image sampling apertures will diverge again so as to isolate the respective components arriving from each of the two lens sectors (figure 18). Within each aperture image in the detector plane are two detectors, one for each of the two sectors (A and B). Output of all 24 of the A detectors is used to construct the A signature; the 24 B detectors are read to form the B signature (reference 39).

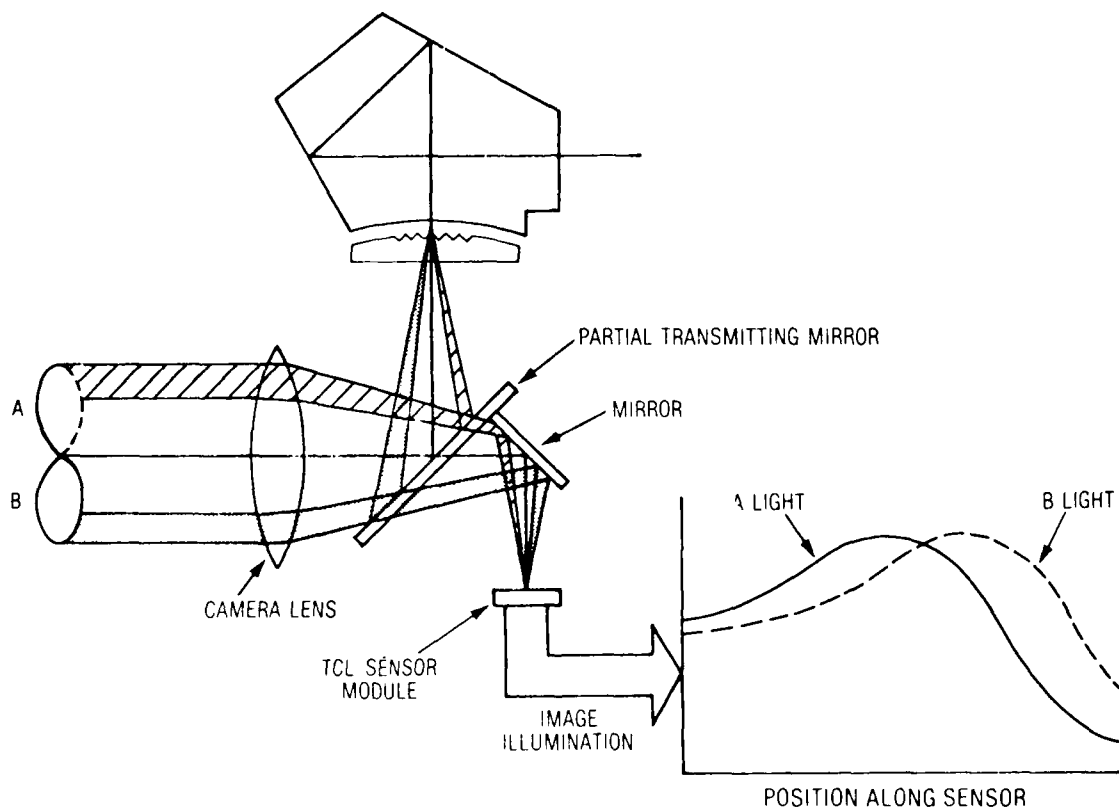


Figure 17. Light from two separate sectors of the same lens is compared to determine the position of best focus in the TCL Autofocus System. (Courtesy Honeywell Corporation)

The signatures of light passing through the two camera lens sectors can then be compared and analyzed. The distance between these lens sectors is the base of triangulation for determining range to the subject. Which signature appears to be leading the other and to what degree indicates how far and in what direction the lens must be moved in order to bring the images into superposition. The output of the CCD detector array is fed to a CMOS integrated circuit which contains the CCD clock circuitry and an A/D convertor which digitizes the analog output for further processing by a dedicated logic algorithm processor.

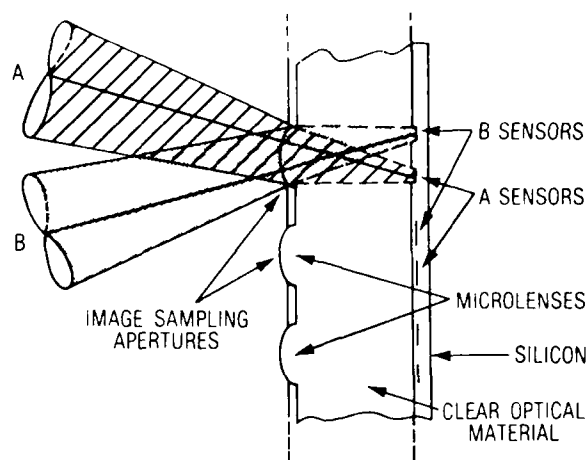


Figure 18. A row of microlenses focuses light on the pairs of detectors, forming two separate signatures for comparison.
(Courtesy Honeywell Corporation)

The TCL System can sense that the image is in focus to where the plane of the image is within 0.05 millimeters of the position of correct focus (reference 39). This can be directly converted to range resolution through the standard lens equation and varies with the focal length of the lens used. The detector pairs in the TCL system can discriminate light differences of one part in 100; the human eye is limited to 1 part in 10 (reference 39). The system operates on a 5-volt power supply, and the sensor and companion ICs together draw less than 60 milliwatts. The TCL system can provide low-cost, noncontact distance sensing for robotic applications, provided the scene being viewed has sufficient contrast.

Point of Contact

Honeywell Visitrionics
P.O. Box 5077
Englewood, Colorado 80155
(303) 850-5050

3.1.8 Laser Photonics' YQF-113 Laser Rangefinder

The YQF-113 is a low-cost, rugged, reliable laser energy source developed by Laser Photonics, Inc. of Orlando, Florida, to meet a wide variety of applications. Potential uses include target designation, surveying, and rangefinding. The system is composed of several modules (i.e., transmitter, power supply, and cooling) which can be assembled into a compact, self-contained unit or separated into individual components, permitting the sensor to assume multiple configurations tailored to the needs of the user. An optional rangefinding module is available with the device and consists of a receiver-detector and a counter which are typically colocated with the transmitter module.

The system, when set up as a rangefinder, emits a high powered, short-duration pulse at a maximum rate of 30 pulses per second. The receiver/counter elements detect the returned energy and time the delay to determine distance to an object by time-of-flight methods. Ranging accuracy is rated at ± 1 meter, with a range increment of 1 meter. The maximum range for the sensor is rated at 30 kilometers; however, the actual achievable range is dependent on meteorological visibility. This means that the YQF-113 can detect and measure the distance to most objects which can be seen by the human eye.

YQF-113 can detect and measure the distance to most objects which can be seen by the human eye through prevailing atmospheric conditions. For example, on a standard clear day with visibility approaching 23 kilometers, ranging is effective out to about 20 kilometers; on a typical hazy day with a visibility of 5 kilometers, effective range is reduced to about 4 kilometers.

The sensor has been specifically designed to operate effectively with specially painted or disguised military targets. The system can detect a 1 square meter, low-reflectivity airborne target (the worst case) at 7.5 kilometers under standard clear day conditions. This feature results in improved performance against natural targets like trees, rocks, and ground. Performance is also dependent on object size: targets which intercept the entire laser beam reflect the most energy while smaller targets result in energy being lost to the background.

The long ranging distances achievable with the YQF-113 rangefinder are partially due to the use of an avalanche photodiode detector capable of nanowatt sensitivities, with narrow bandpass filtering corresponding to the transmission wavelength. There is no built-in scanning capability with the sensor; therefore, it must be mechanically positioned to collect data. Other features include an embedded controller based on the Intel 8751 microprocessor, a proprietary control architecture built upon the Internal Laser Computer Bus (ILCB), and a built-in system test capability.

Selected Specifications (rangefinder configuration)

Maximum Range	30 kilometers
Minimum Range	30 meters
Range Increment	1 meter
Range Accuracy	± 1 meter
Light Source	Laser diode operating at 1.064 nanometers
Output	150 millijoules at 10 and 20 Hz, 90 millijoules at 30 Hz
Standard Divergence	2 milliradians
Field of view	2 milliradians
Power Requirements	28 volts at 12 Amps (20 Amps Peak)
Operating Temperature	-20 to + 55 degrees Centigrade
Enclosure	7.0 x 7.1 x 18.0 inches
Weight	24 pounds

Point of Contact

Laser Photonics, Inc
12351 Research Parkway
Orlando, Florida 32826
(305) 281-4103

3.1.9 Robot Defense Systems OWL

The OWL is a computer-controlled, three-dimensional, laser-based imaging device intended initially for intrusion detection applications (reference 40). The system, developed by Robot Defense Systems of Thornton, Colorado, mechanically scans a wide field of view in a raster sequence to produce images which are automatically analyzed in order to map a scene and detect objects. The observed objects are then categorized by threat level and an alarm is triggered if the threat is high. The entire process of data collection, analysis, and classification occurs at a rate of approximately 1.5 frames per second. The sensor determines range through phase shift measurement, as well as the returned signal amplitude of the scanned points, which allows it to display the outline and dimensions of an object.

The maximum range for the system is 140 feet; objects larger than 3 inches can be detected at a distance of 70 feet. Horizontal scanning is performed by a pair of synchronized, counter-rotating, mirrored wedges; one wedge directs the transmitted beam while the other collects the returning energy.

field of view of 256 by 128 pixels. The laser light source, classified as eye safe due to the constant scanning motion of the beam, allows operation in about all environmental conditions (including adverse weather, smoke, and darkness). Computer control of the imager is centralized and capable of overseeing up to 100 separate scanners. GOULD, Inc., Defense Electronics Division is currently considering this sensor for collision avoidance and navigation applications on future autonomous land-based vehicle work.

Selected Specifications

Maximum Range	140 feet
Minimum Range	10 feet
Light Source	Laser diode operating at 800 nanometers
Output	
Beam Divergence	< 0.2 degrees
Field of view	45 degrees(horizontal) 30 degrees (vertical)
Scan Rate	5760 degrees/second (horizontal) 30 degrees/second (vertical)
Power Requirements	150 watts at 24 volts
Operating Temperature Range	-20° to +140° F
Enclosure	1728 cubic inches
Weight	

Point of Contact

NOTE: Company is no longer in business. Included for information purposes only.

Robot Defense Systems, Inc.
471 East 124th Avenue
Thornton, Colorado 80241

3.1.10 NAMCO LASERNET Smart Sensor

NAMCO Controls of Mentor, Ohio, has developed a multifunction laser-based intelligent sensor system intended for applications in industrial environments. Known as LASERNET, the sensor is an active scanning device which requires retroreflective targets in order to measure range and angular position. It is also possible to specifically identify objects through the use of coded targets.

A helium-neon (HeNe) laser source, photodetector, mechanical scanner, beam forming optics, and control electronics are housed in an enclosure measuring 5 by 6.5 by 3.15 inches. The detector is a photodiode with an operational bandwidth of 1.0 MHz, tailored to receive inputs across the visible red and infrared light region of the spectrum. A servo-controlled rotating mirror horizontally pans the laser beam through an arc of 90 degrees (45 degrees either side of the center) at a rate of 20 scans per second. Directional mirrors route the beam from the lasertube to the scanning mirror; a collecting lens focuses the return signal onto the photodetector.

Retroreflectors positioned within the sensor's environment are necessary for the effective application of the LASERNET ranging system. A standard retroreflective target is provided by the developer, essentially a 4- by 4-inch-square surface of corner cube prisms with an overall 90-percent reflection coefficient. The LASERNET system operates by panning a beam of light across the scene at a constant rate through a 90-degree field of view. When the laser beam sweeps across a retroreflective target, a return signal of finite duration is sensed by the detector. Since the targets are all the same size, the return generated by a close target will be of longer duration than that from a distant one (figure 19A). In effect the target appears larger.

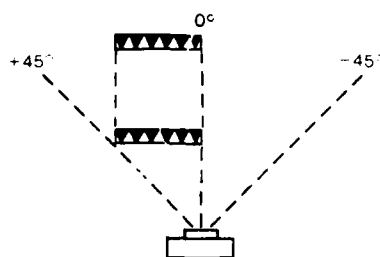


Figure 19A. Target range.

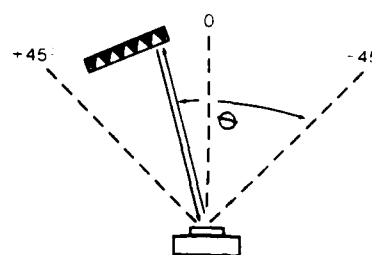


Figure 19B. Target bearing.

Range is calculated from the equation (reference 41)

$$d = \frac{W}{2 \tan (V T_a / 2)}$$

where

- d = range to target
- W = target width
- V = scan velocity
- T_a = duration of the returned pulse.

Because the target width and angular scan velocity are known, the equation reduces down to an inverse function of the pulse duration, T_a . With 4-inch targets, the effective range of the sensor is from 1 to 20 feet, with an accuracy of ± 4 percent at 20 feet and a range resolution of 9.6 inches at 20 feet down to 0.1 inch at 1 foot. LASERNET produces an analog output ranging from 0 to 10 volts over the range 0 to 20 feet.

Angle measurement is initiated when the scanner begins its sweep from the right; the laser strikes an internal synchronization photodetector which starts a timing sequence. The beam is then panned across the scene until reflected by a retroreflective target in the field of view. The resulting returned signal is detected by the sensor, terminating the timing sequence (figure 19B). The elapsed time is used to calculate the angular position of the target in the equation (reference 41):

$$\theta = (V T_b) - 45$$

where

- θ = target angle
- V = scan velocity (7200 degrees/sec)
- T_b = interval between scan initiation and target detection.

This angle calculation determines the position of the leading edge of the target with respect to the midpoint of the 90-degree scan. Therefore, to measure to the center of a target an offset based on the target size must be added. The angular accuracy for LASERNET is ± 3 percent and the angular resolution is 0.1 degree for the 90-degree sweep. The output is an analog voltage ranging from 0 to 10 volts over the range of from -45 to +45 degrees.

By masking a target in specific ways, it is possible to obtain some limited height information, as well as, range, and angular position. With a mask that falls along the diagonal of the square and blocks the lower left portion of the target, the height and angle can be measured. This configuration is ideal when the range to a target is a known constant. The height is a function of the duration of the returned pulse which varies with the vertical position of the laser scan. The leading edge of the target is not masked so the angle calculation is identical to that discussed above.

Note that all the above calculations assume that the target is positioned perpendicular to the angle of incidence of the laser source. If a target happens to be rotated or otherwise skewed away from the perpendicular it will appear narrower than actual with a resultant range measurement error. Errors in angle determination also occur because the leading edge is either positioned in front of or behind the center of the target.

With the proper placement of retroreflective targets or tape, the LASERNET system can guide AGVs using wall-following, center-of-the-path, or track-following methods. The sensor is also capable of aligning the lifting mechanisms of automated conveyors to desired storage locations, as well as providing identification of the contents of a particular location when coded targets are used. Because of the requirement for fixed-position retroreflectors, the use of such a system in mobile applications will in general be limited to facility robots which work in known environments.

Point of Contact

NAMCO Controls
7567 Tyler Boulevard
Mentor, Ohio 44060
1-800-NAMTECH

3.1.11 ERIM ASV/ALV Sensor

The Adaptive Suspension Vehicle (ASV) being developed at Ohio State University and the Autonomous Land Vehicle (ALV) being developed by Martin Marietta Denver Aerospace are the premier autonomous mobile robot projects sponsored by the Defense Advanced Research Projects Agency (DARPA) under the Strategic Computing Program. In support of these efforts, the Environmental Research Institute of Michigan (ERIM) was tasked to develop an advanced, three-dimensional vision system to meet the close-in navigation and collision avoidance needs of a mobile platform. The initial design, which is now commercially available under license from ERIM to the Daedalus Corporation, Ann Arbor, Michigan, is known as the Adaptive Suspension Vehicle Sensor. The sensor operates on the principle of optical radar and determines range to a point through the phase shift measurement techniques using a continuous wave laser source.

The ranging sequence begins with the transmission of a modulated laser beam which illuminates an object and is partially reflected back to the receiver, where the returning light strikes the detector, generating a representative signal. This signal is amplified and filtered to extract the modulation frequency. At this point, the amplitude of the signal is picked off to produce a reflectance image (used to produce a video image for viewing or for two-dimensional image processing.) A reference signal is then output by the modulation oscillator and both the detector and reference signals are sent to the comparator electronics. The CW laser is modulated at an RF frequency (70 MHz) and it is the detection of phase shift on this signal, not the optical carrier, that is used to derive range. This phase difference is determined by a time measurement technique where the leading edge of the reference signal initiates a counting sequence which is terminated when the leading edge of the returned signal enters the counter. The resulting count value is a function of the phase difference between the two signals and is converted to an 8-bit digital word representing the range to the scene.

Three-dimensional images are produced by the ASV sensor through the use of scanning optics. The mechanism consists of a nodding mirror and a rotating polygonal mirror with four reflective surfaces (figure 20). The polygonal mirror pans the transmitted laser beam in azimuth across the ground, creating a scan line at a set distance in the front of the vehicle. The scan line is deflected by the objects and surfaces in the observed region and forms a contour of the scene across the sensor's horizontal field of view. The third dimension is added by the nodding mirror which tilts the beam in discrete elevation increments. A complete image is created by scanning the laser in a left-to-right and bottom-to-top raster pattern. The returning signals share the same path through the nodding mirror and rotating polygon (actually slightly offset), but are split off through a separate optical chain to the detector. The scan

rate for the sensor is 180 lines per second and is a function of the field of view and desired frame rate, determined by the vehicle's maximum forward velocity (10 feet/sec in this case). The size, weight, and required velocities of the mirrors precluded the use of galvanometers in the system design: the rotating mirror is motor driven and the nodding mirror is servo driven.

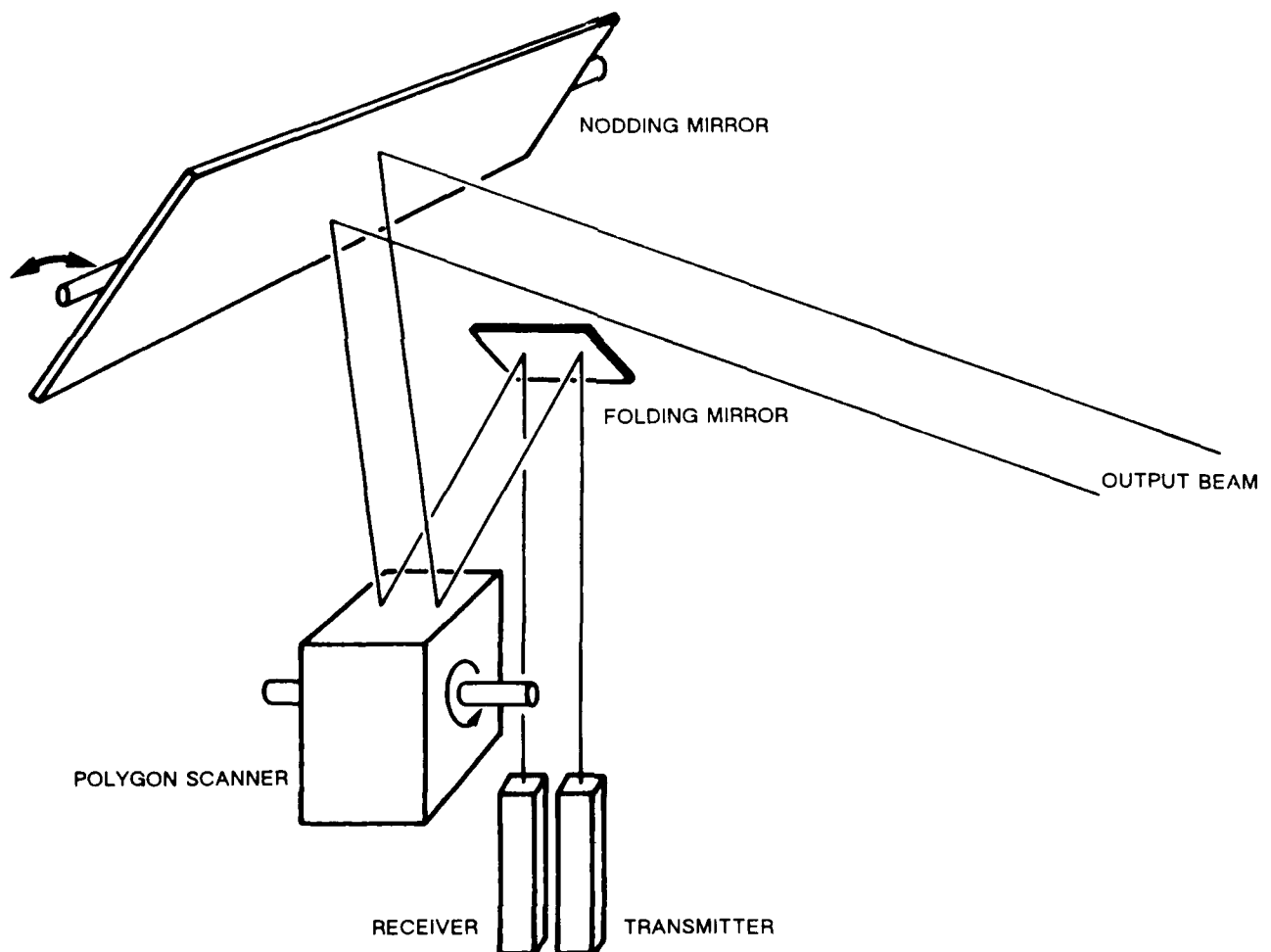


Figure 20. Scanning and nodding mirror arrangement in the ERIM laser rangefinder.
(Courtesy Environmental Research Institute of Michigan)

The output beam is produced by a gallium arsenide (GaAs) laser diode emitting at a wavelength of 820 nanometers. The small size, internal modulation, low temperature, and limited eye hazard of this source resulted in its selection over an alternative carbon dioxide laser used in a trade-off analysis. The only significant drawbacks for the GaAs device were reduced effectiveness in bright sunlight, and only fair penetration capabilities in fog and haze. Collimating and expansion optics were required by the system in order to produce a 6-inch diameter laser footprint at 30 feet, which is the effective operating range of the sensor. The major factor limiting the useful range of the system is the measurement ambiguity which occurs when the phase difference between the reference and returned energy exceeds 360 degrees.

The detector is a silicon avalanche photodiode matched to the laser wavelength. The laser source, detector, scanning optics, and drive motors are housed in a single enclosure. The device is designed to be situated at a height of 8 feet in order to look down upon the field of view. From this vantage point the laser strikes the ground between 2 feet and 30 feet in front of the vehicle; at 30 feet, the horizontal scan line is 22 feet wide. The 2-Hz frame rate for the system creates a new image of the scene for every 5 feet of forward motion at the vehicle's maximum designed rate of speed (10 feet/sec).

Following the design and fabrication of the ASV sensor, ERIM undertook the task of developing a similar device for DARPA's Autonomous Land Vehicle known as the ALV Sensor. The two instruments are essentially the same in configuration and function, but with modified specifications to meet the needs of the individual mobile platforms. The following selected specifications for each device illustrate their differences.

Selected Specifications

	<u>ASV</u>	<u>ALV</u>
Ranging Technique	Phase Shift	Phase Shift
Field of View	80 degree horizontal 60 degree vertical	80 degree horizontal 30 degree vertical
Beamwidth	1 degree	1/2 degree
Frame Rate	2 frames/second	2 frames/second
Scan Lines Per Frame	128	64
Pixels Per Scan Line	128	256
Maximum Range	32 feet	64 feet
Depression Angle (Top of vertical scan)	-15 degrees	-15 degrees
Vertical Scan Increment	10 degrees	20 degrees
Laser Wavelength	820 nanometers	820 nanometers
Beam Size	0.5 feet @30 feet	0.44 feet @ 50 feet
Power Requirements	24 volts 450 watts	24 volts 450 watts
Enclosure	14 x 26 x 22 inches	14 x 29 x 22 inches
Weight	85 pounds	85 pounds

Point of Contact

Environmental Research Institute of Michigan
Box 8618
Ann Arbor, Michigan 48107
(313) 994-1200

3.1.12 CLS Laser Ranger

Chesapeake Laser Systems of Lanham, Maryland, offers an active laser-based triangulation ranging system to measure the position of an object. The unit employs a laser diode emitting up to 30 milliwatts, a linear CCD detection array, and a high speed preprocessor and microprocessor-based control system.

Noteworthy features include the following:

1. Dynamic exposure control that allows the system to function effectively over five orders of magnitude light intensity.
2. The temperature stability of a linear CCD array allows operation in hostile environments without recalibration.
3. Smart electronics allow the gauge to adapt to changing conditions.

The optics and electronics are housed in a NEMA 12 drip-proof enclosure, with the optics protected by an over pressure "air curtain" for applications involving extremely hostile environments. Several housing sizes are available depending on the range or accuracy desired. The CLS Laser Ranger can be configured to measure ranges of 10 feet or more.

Selected Specifications (LTG-2000 Series)

Ranging Technique	Active Triangulation
Maximum Range	10 feet plus
Size	6 x 9 x 2 inches
Weight	4 pounds
Light Source	Laser diode operating at 820 nanometers
Power Requirements	

	<u>Option 1</u>	<u>Option 2</u>
Distance to Center of Range	2 feet	0.5 feet
Range	2 feet	1 inch
Accuracy	0.005 to 0.040 inch	0.001 inch

Point of Contact

Dr. J. Bradford Merry
Chesapeake Laser Systems, Inc.
4473 Forbes Boulevard
Lanham, Maryland 20706
(301) 459-7977

3.1.13 CLS Laser Profiler

Chesapeake Laser Systems has developed a laser-scanning range measurement system using a solid-state beam deflector (figure 21). This system has a speed and accuracy advantage over systems relying on mechanical scanning mechanisms or CCD arrays to acquire three-dimensional data. The solid state device allows random beam positioning with a 10 microsecond response time (reference 43).

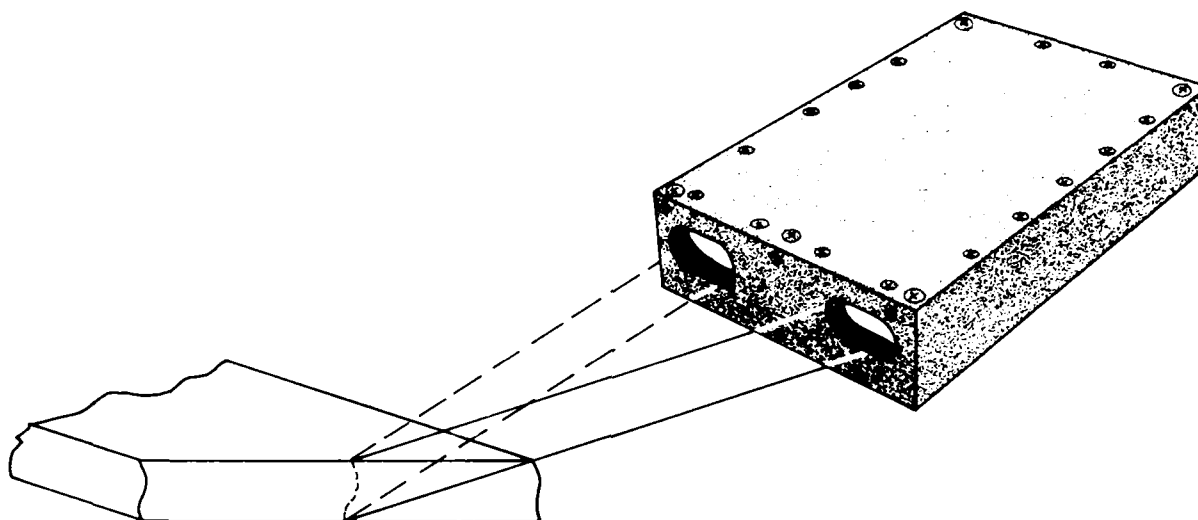


Figure 21. Chesapeake laser-scanning range measurement system.

This electro-optic camera was developed to replace conventional TV cameras in three-dimensional vision systems. The Chesapeake Profiler performs like a randomly accessible 1000 by 1000 two-dimensional array. Most conventional vision systems use a small CCD television camera that collects visual information. This information is then fed to a computer which uses pattern recognition software to obtain geometrical data. Processing involves a minimum of 65,000 pieces of information which must be digitized and sorted, a relatively difficult and time consuming task which can take on the order of 0.1 or more seconds. The electronic and software complexity of the CCD TV approach unnecessarily limits the speed and precision of machine vision (reference 43).

The solid state scanning mechanism removes these limitations by collecting only the useful information from the scene being viewed; processing time is cut to 0.001 second. The LPG-4010 shown in figure 21 gives high accuracy measurement over ranges out to 1.5 inches. A second unit is now under development which will provide distance measurement capability over ranges from 4 to 5 feet, with a resolution of 0.25 inch.

Selected Specifications (LPG-4000 Series)

Ranging Technique	Active triangulation
Standoff	2 to 20 inches
Range	0.5 to 2 inches
Accuracy	0.001 to 0.032 inch
Resolution	1:256 to 1:2000
Points of Profile	1 to 1000 (programmable)
Data rate	1 to 10 kHz
Size	3 x 6 x 8 inches
Weight	
Power Requirements	115 VAC or DC (+28V, +15V, +5V)

Point of Contact

Dr. J. Bradford Merry
Chesapeake Laser Systems, Inc.
4473 Forbes Blvd.
Lanham, Maryland 20706
(301) 459-7977

3.1.14 CLS Laser Coordinate Measuring System CMS-100

Chesapeake Laser Systems has recently completed development of a laser-based tracking interferometer system that can measure the location of a moving object to better than 10 microns over a volume of 3 by 3 by 3 meters (references 20 and 44). The system uses a servo-controlled beam steering system to track a randomly moving target. (Standard interferometric ranging works only with non-rectilinear straight-line motion as discussed in Section 2.1.6.)

Figure 22 shows the CMS-1000 using one or three laser beams to track a retroreflective target attached to the moving object. The tracking interferometer is rigidly fixed to the edge of the work area. After a brief calibration routine, the CMS-1000 continuously measures the distance to the retroreflector and calculates the x, y, and z coordinates of the robot arm at a 50 Hz-rate.

To get positional accuracy of 0.001 inch at a distance of 10 feet using a conventional angle-measuring triangulation scheme requires an angle measurement accuracy of 1.7 seconds of arc. It is the experience of personnel in the optical instrumentation industry that such angular precision is not practical for distances over 10 feet regardless of the precision of the shaft angle encoder used. The angular error is largely due to servo-loop tracking error (± 5 seconds of arc), atmospheric turbulence and gradient index effects due to temperature variations (± 10 seconds of arc), laser pointing inaccuracies (± 2 seconds of arc), and laser spot position uncertainty on the tracking mirror (± 2 seconds of arc).

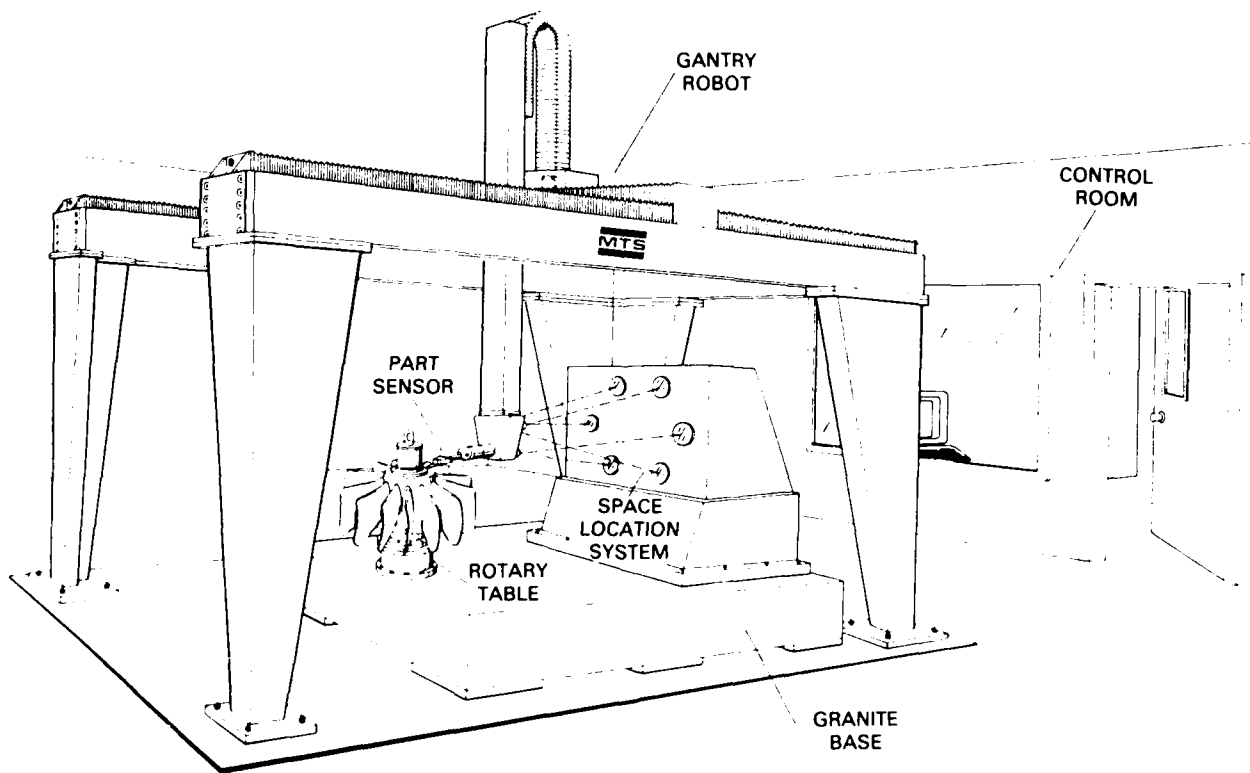


Figure 22. Chesapeake Laser's CMS-1000 Space Location System installed on the Intelligent Robotic Inspection System built for the Navy by MTS Systems Corporation. (Courtesy MTS Systems)

Instead of measuring angles, the CMS-1300 uses a system of three tracking interferometers to measure distance to a special retroreflector via trilateration techniques. Such a system is inherently more accurate than any technique which incorporates angle measurement for the reasons mentioned above.

When angular measurements are used, position errors appear as $r d\theta$, where r is the radial distance from the tracker to the retroreflector, and $d\theta$ is the angular error. For example, an angular error of 20 seconds of arc over 10 feet shows up as a position error of 1 microinch.

In the trilateration scheme, no angles are measured, only distances (i.e., $r1$, $r2$, and $r3$). The position error shows up as

$$\text{error} = r (1 - \cos d\theta) = r d\theta^2$$

which is orders of magnitude smaller than $r d\theta$.

Point of Contact

Dr. J. Bradford Merry
Chesapeake Laser Systems, Inc.
4473 Forbes Blvd.
Lanham, Maryland 20706
(301) 459-7977

3.1.15 VRSS Automotive Collision Avoidance Radar

One of the first practical short-range collision avoidance radar systems for use on ground vehicles was developed by Vehicle Radar Safety Systems of Mt. Clemens, Michigan, (reference 45). This specially modified Doppler radar unit is intended to alert automobile drivers to potentially dangerous situations. A grill-mounted miniaturized microwave radar antenna sends out a unique "narrow-beam" signal which detects only those objects directly in the path of the vehicle, ignoring objects (such as road signs and parked cars) on either side. When the radar signal is reflected from a slower moving or stationary target, it is detected by the antenna and passed to an under-the-hood electronic signal processor.

The signal processor continuously computes the host vehicle speed and acceleration, distance to the target, its relative velocity, and its acceleration. If these parameters collectively require the driver to take any corrective or precautionary action, a warning buzzer and signal light are activated on a special dashboard monitor. An "alert" signal lights up when an object or slower moving vehicle is detected in the path of the host vehicle. If the target range continues to decrease, and the system determines that a collision is possible, a "warning" light and buzzer signal the driver to respond accordingly. If range continues to decrease with no reduction in relative velocity, then a "danger" light appears to indicate the need for immediate action.

A sophisticated filter in the signal processor provides for an optimum operating range for the system, based on the relative velocity between the vehicle and the perceived object. The response "window" corresponds to a calculated difference in speed of between 0.1 and 30 mph (reference 45). If the speed differential exceeds 30 mph, the filter circuit delays signals to the dashboard monitor. This helps to filter out false signals and signals that might otherwise be caused by approaching vehicles when passing another vehicle on a two-lane highway.

The VRSS collision warning system has been extensively tested over a million miles of driving conditions in fog, rain, snow, and ice with good results. The present model was perfected in 1983 after 36 years of research, and approved by the FCC in 1985. Although aimed at the bus and trucking industries, the low-cost unit (\$965) offers convincing proof that small, low-power radar systems offer a practical alternative to ultrasonic rangefinders for the collision avoidance needs of a mobile robot, particularly in outdoor scenarios.

Point of Contact

Charles Rashid
Vehicle Radar Safety Systems
10 South Gratiot, Suite 303
Mt. Clemens, Michigan 48043
(313) 463-7883

3.2 Under Development

3.2.1 FMC Sonic Imaging Sensor

The Sonic Imaging Sensor is an obstacle detection and collision avoidance sensor designed by the FMC Corporation for their research effort involving autonomous vehicles. The device is essentially a phased-array sonar system with 4 piezoelectric transmitters and a linear array of 16 detector microphones. The transmitters emit in the audible range and are therefore classified as sonic. Most of the major sensing components are commercially available and the absence of moving parts makes the instrument highly rugged. The system functions as a time-of-flight ranging device where sound pulses are sent out and their echoes from objects are detected, operating in the region between 15 and 33 meters (i.e., blind spot out to 15 meters).

The phased-array circuitry electronically scans the transmission across a 120-degree field of view and creates a new terrain image consisting of 280 pixel elements every 200 milliseconds. The minimum object size seen by the sensor is 0.5 meter on a side. Angular resolution for the system is on the order of ± 5 degrees, while the distance resolution is ± 0.7 meter. The device in its current configuration is elevated above the ground between 6 and 12 feet and mounted on an Army M113 Armored Personnel Carrier used by FMC as their autonomous mobile testbed. The resultant terrain image data from the sensor are input into the autonomous navigation controller of the platform and used to help the vehicle avoid obstacles (reference 46).

The system has been demonstrated effectively at a speed of 5 mph and future tests will attempt to reach the goal of 15 mph. This is considered to be the limit of this current sensor because of the excessive vehicle noise at higher velocities which saturates the signal processing electronics. This is an experimental unit only and not likely to be pursued for practical implementation due to problems discussed involving poor resolution and susceptibility to ambient noise interference.

Point of Contact

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Central Engineering Laboratories
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Santa Clara, California 95052
(408) 289-2731

3.2.2 Optima Ultrasonic Ranging System

Optima Systems' Ultrasonic Height Sensor is a field prototype noncontact ranging and velocity sensing unit. The sensor hardware consists of three major elements: an ultrasonic transmitter, an ultrasonic receiver, and a central control unit. The transmitter emits an ultrasonic waveshape which is directed towards the target surface. The receiver detects the ultrasound reflected by the target. The control unit produces a distance or height measurement based upon the time of flight required for the emitted signal to travel to the target and be reflected back to the receiver. A velocity measurement is made based upon any Doppler shift present between the emitted and detected ultrasonic frequencies. The prototype provides two analog outputs corresponding to the target distance and to the velocity with respect to the target. The two outputs can be read with any voltage measurement instrument or can be easily interfaced to any microprocessor based hardware.

The receiver and transmitter are each housed in a 7- by 5- by 3-inch enclosure. These may be mounted remotely from the control unit. The central control unit is housed in a 12- by 10- by 5-inch steel enclosure. The entire system weighs approximately 25 pounds. Production models of the system could be made smaller and lighter with a more compact and efficient electronic circuit layout. The unit can be powered externally or can be operated from the internal rechargeable batteries.

The unit is not sensitive to background noise and is designed to operate under a variety of environmental conditions. The unit has been designed to withstand high shock and to operate under

dusty and noisy conditions. The ability to withstand severe operating conditions makes the ultrasonic system especially suited to other outdoor and industrial applications. Several possible applications include the measurement of payload heights to assist construction and loading dock crane operators, the measurement of the height of corn or grain in storage silos, and use in collision avoidance systems for vehicles and robots. In a collision avoidance system, the ultrasonic sensor could provide both range and relative velocity measurements of both moving and stationary obstacles.

Point of Contact

Jack Echiam
Optima Systems, Inc.
1 North Avenue
Burlington, Massachusetts 0180
(617) 273-3055

3.2.3 Optima Nonecho Ultrasonic Ranging System

A master/slave nonecho TOF ranging unit was developed by Optima Systems, Inc. to measure distances ranging from 1 foot to beyond 250 feet through the use of ultrasonics. Accuracy over this range is approximately 0.01 percent. This far surpasses the range normally considered viable for acoustic ranging systems. Most pulse-echo systems, such as those found in autofocus cameras, are limited to approximately 35 feet.

The ranging system is able to achieve accurate measurements over these distances by using a combination of radio frequency and ultrasonic signals. A central processing unit (CPU) controls the operation of an RF transmitter and an ultrasonic receiver. Signals sent out by the RF transmitter are received and decoded by a remotely located radio receiver. The receiver is connected to an ultrasonic transmitter, which in turn transmits an acoustic signal back toward the CPU. This signal is received and decoded by the ultrasonic receiver. The CPU then performs a time-of-flight calculation to determine the distance between the acoustic transmitter and the acoustic receiver. Distances are then displayed on an LED readout in feet or meters.

The system is capable of controlling up to three ultrasonic receivers, each of which in turn may have its own battery operated ultrasonic transmitter. This allows up to three distances to be simultaneously calculated. A calibrated thermistor is used to determine ambient temperatures so that sound velocity, which is strongly dependent on temperature, may be accurately determined.

Point of Contact

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Burlington, Massachusetts 01803
(617) 273-3055

3.2.4 Odetics Scanning Laser Rangefinder

Odetics Incorporated of Anaheim, California, recognized the need for an adaptive and versatile vision system for mobile robot navigation while developing ODEX 1, a six-legged, walking robot. The ensuing 3-year research effort resulted in a scanning laser rangefinder capable of producing three-dimensional images of an observed scene. The system ranges to individual points by phase shift measurement, constructing range pictures by panning and tilting the sensor across the field of view. This technique was selected over alternatives including acoustic ranging, stereo vision, and structured light triangulation because of the inherent accuracy and simplified interface to robotic systems.

The imaging system consists of two major subelements: the scan unit and the electronics unit (figure 23). The scan unit houses the laser source, the photodetector, and the scanning mechanism. The laser

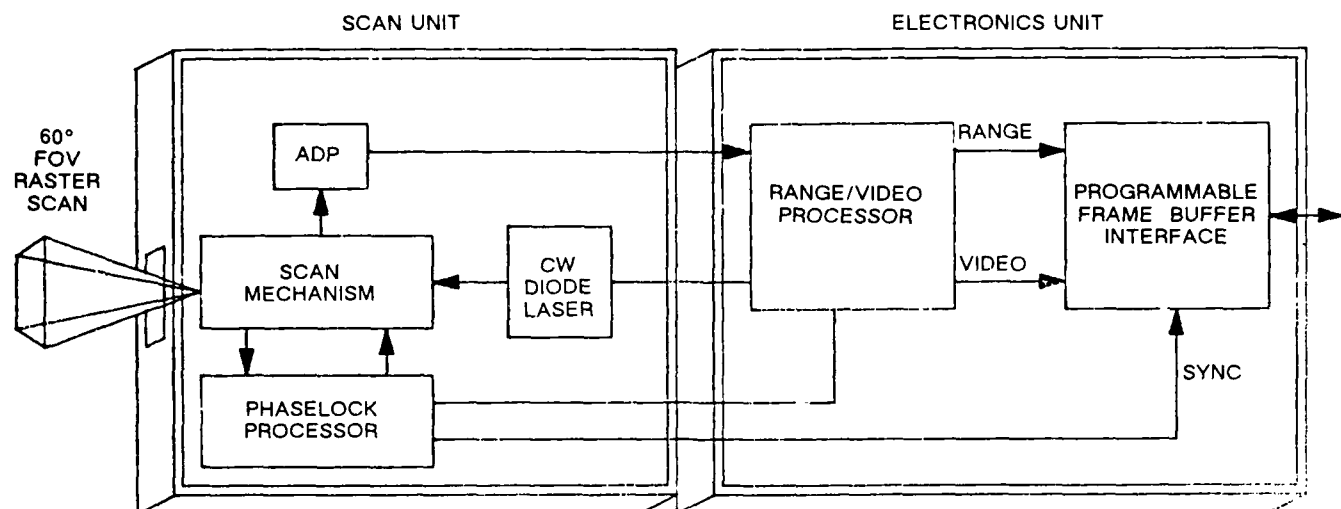


Figure 23. Block diagram of Odetics Scanning Laser Rangefinder. (Courtesy Odetics, Inc.)

source is a continuous wave, gallium aluminum arsenide (GaAlAs) laser diode emitting at a wavelength of 820 nanometers. The power output is adjustable under software control between 1 to 50 milliwatts. Detection of the returned energy is achieved through use of an avalanche photodiode whose output is routed to the phase measuring electronics. The scanning hardware consists of a rotating polygonal mirror which pans the laser beam across the scene, and a planar mirror whose back and forth motion tilts the beam for a realizable field of view of 60 degrees in azimuth and 60 degrees in elevation. The scanning sequence follows a raster scan pattern and can illuminate and detect an array of 128 by 128 pixel elements at a frame rate of 1.2 Hz (835 milliseconds per frame).

The second subelement, the electronics unit, contains the range calculating, video processor, and programmable frame buffer interface (PFBI). The range and video processor is responsible for controlling the laser transmission, the activation of the scanning mechanism, the detection of the returning energy, and the calculation of range values. Distance is calculated through a proprietary Odetics phase detection scheme, reported to be high speed, fully digital, and self-calibrating with a high signal-to-noise ratio. The minimum observable range is 1.5 feet, while the maximum range without ambiguity due to phase shifts greater than 360 degrees is 30.74 feet.

For each pixel, the processor simultaneously outputs a range value and a video reflectance value. The video data are equivalent to that obtained from a standard black and white television camera, except that interference due to ambient light and shadowing effects has been eliminated. The format for these outputs is a 16-bit data word consisting of the range value in either 8 or 9 bits and the video information in either 8 or 7 bits, respectively. The resulting resolution for the system is 1.44 inches when using the 8-bit format, and 0.72 inch with 9 bits.

The PFBI provides interim storage of the data and can execute single word or whole block direct memory access transfers to external host controllers under program control. Information can also be routed directly through the PFBI to a host without being held in the buffer. Currently, the interface is designed to support VAX, VME-Bus, Multibus, and IBM-PC/AT equipment.

Selected Specifications

Ranging Technique	Phase Shift Measurement
Field of view	60 degrees (horizontal)
	60 degrees (vertical)
Frame Size	128 x 128 pixels
Frame Rate	835 milliseconds/frame
Range Resolution	1.44 inches (8 bit), 0.72 inch (9 bit)
Ambiguity Range	30.74 feet
Minimum Range	1.5 feet
Laser Source	GaAlAr laser diode operating at 820 nanometers
Enclosure	9 x 9 x 9.25 inches (scan unit)
	7 x 7 x 2.5 inches (electronics unit)
Weight	28 pounds (scan unit)
	3 pounds (electronics unit)
Power Requirements	28 VDC at 50 watts

Point of Contact

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1515 South Manchester Avenue
Anaheim, California 92802
(714) 758-0300

3.2.5 RVSI Ship Surface Scanner

Robotic Vision Systems, Inc. developed, under contract to the Navy, a laser-based noncontact measuring device known as the Ship Surface Scanner, intended for use in automated surveying of the interior spaces of ships. The sensor is designed to support ship overhaul and repair functions by reducing the required man-hours for measurement, documentation, and planning to allow structures to be accurately prefabricated for installation during overhaul. The tripod-supported, three-dimensional scanner employs a GaAlAs laser diode which yields an 1/8-inch-diameter footprint at 12 feet.

Figure 24 shows distance is measured by simple triangulation; a two-dimensional solid state camera is mounted 35 inches away from the laser source. The stepper-motor-driven scanner pans a horizontal field of view ± 35 degrees in elevation. The azimuth scan rate for the system is 10 degrees per second, with just 1 second required to step to the next elevation line. The system has an effective depth of field of 8 feet between the distances of 4 and 12 feet, with accuracies varying from 0.05 inch at 4 feet to 0.225 inch at 12 feet.

In order to accurately survey entire interior spaces, several scanners can be placed in a circular arrangement so that their collective fields of view traverse 360 degrees. This can also be accomplished by moving a single sensor to multiple positions. The measurement data collected will be used for two purposes. First, the range data will be converted into information for input into computer-aided design (CAD) systems intended to ease the burden of ship design. Second, the high resolution data will be used to produce displays and "as built" drawings of ship compartments.

The Ship Surface Scanner was designed as an interior measurement device with no need for real-time scan rates, but its three-dimensional imaging capabilities make it a possible candidate for robotic applications both indoors and out. An improved, faster scanning version is being evaluated as an object detection, position, and orientation sensor for an automated materials handling system currently under development by the U.S. Army.

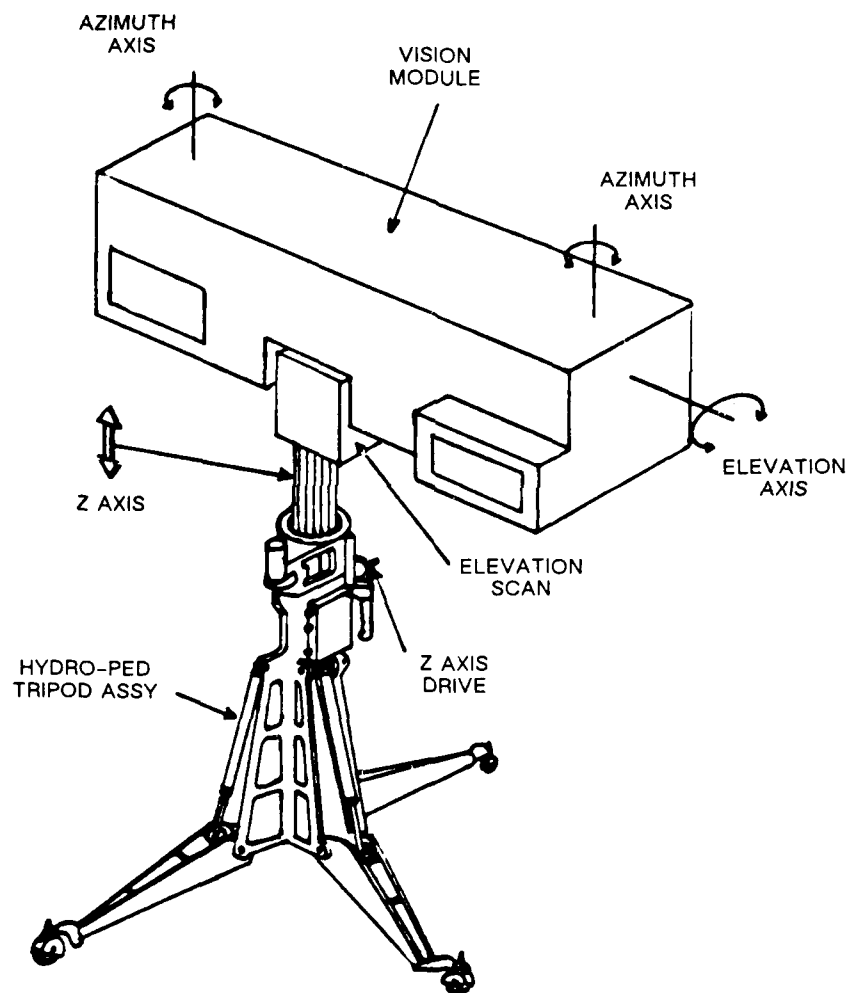


Figure 24. RVS Ship Surface Scanner was designed to digitize the interior of ship spaces for overhaul planning. (Courtesy RVS)

Selected Specifications

Ranging Technique	Triangulation
Field of view	± 35 degrees azimuth ± 35 degrees elevation
Range Resolution	0.050 inch at 4 feet 0.225 inch at 12 feet
Minimum Range	4 feet
Maximum Range	12 feet
Laser Source	GaAlAs laser diode operating at 850 nanometers
Power Requirements	20 Amps at 115 VAC
Enclosure	37 x 5.75 x 7.75 inches
Weight	32 pounds

Point of Contact

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Robotic Vision Systems, Inc.
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3.2.6 NSWC Passive Three-Dimensional Vision

The Passive Three-Dimensional Vision System is an adaptive camera and control system being developed by the Naval Surface Weapons Center in White Oak, Maryland (references 47 and 48). The objective is to create a computer-based vision system and specialized image processor to achieve three-dimensional, near-real-time vision. The initial application was to serve the collision avoidance needs of a mobile robotic platform. The three-dimensional sensor was designed to employ special optical preprocessing techniques to minimize the onboard computational requirements for image understanding.

The Three-Dimensional Camera Subsystem being developed by Associates and Ferren of Wainscott, New York, is a monocular camera system (figure 25) which performs ranging and three-dimensional imaging tasks by use of the swept focus technique discussed in section 2.1.7 of this report (reference 48). The system consists of the swept focus sensor, mounted on a robotic vehicle, in communication with a computer and frame grabber. In order to determine the range to objects in the sensor's field of view, the lens is swept through hundreds of discrete focal positions, remaining at each position for 1/60th of a second, or one video field time. During this time, the analog signal processor integrates the high frequency response in that field. This summation is a measure of the amount of edge information in that range slice and is related to the relative degree of focus (figure 26). The best focus position for an object corresponds to a peak in the high-frequency response with range.

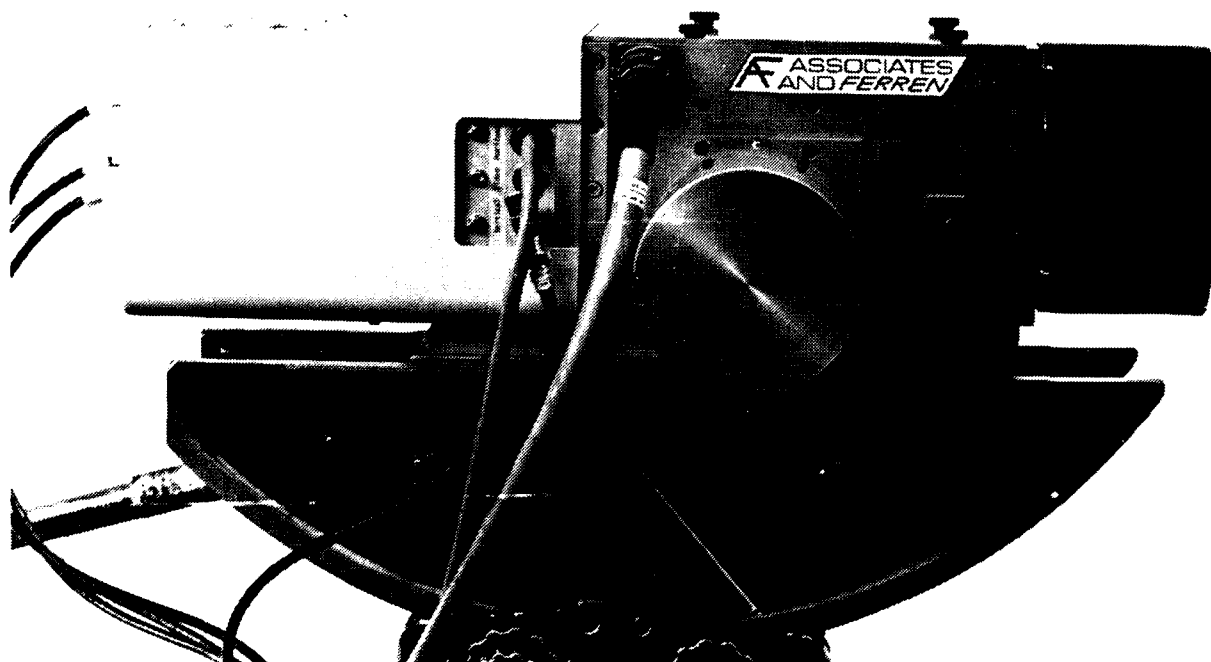


Figure 25. Swept-Focus Camera Subsystem developed for the Navy for passive 3-D vision applications. (Courtesy Associates and Ferren)

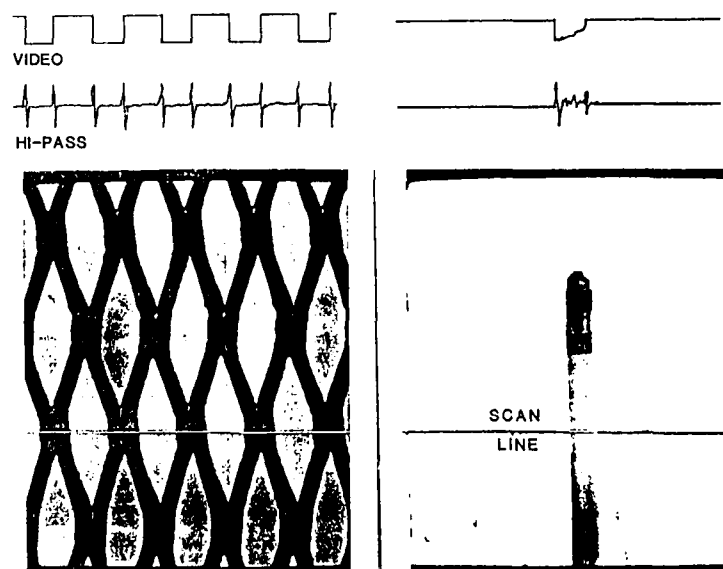


Figure 26. Video and high-pass filter output when viewing a piece of expanded metal (left) and a pencil (right).

Multiple targets at different ranges in the field of view can be accurately located by this technique. To perform the ranging function, only the high-frequency response at each lens position must be recorded. Good accuracy (about 1 inch) and repeatability are obtained with a 600-position scan over a 25-foot-range interval, which takes approximately 12 seconds (figures quoted for a 50-mm/f1.0 lens). Accuracy and resolution vary with range and are greatest at closer range, using the current exponential scan profile. The primary factor limiting the speed of this technique is the video field rate (NTSC Standard). Ranging accuracy and repeatability are dependent upon lens characteristics, specifically on the depth of field of the lens. The shorter the depth of field, the greater the ranging accuracy and resolution of closely spaced targets (section 2.1.7). In practice, the two lenses found to be most useful are a 50 mm/f1.0 and a 105 mm/f1.8, both good quality photographic lenses. The longer lens offers better ranging accuracy and resolution, but has a narrower field of view than the shorter lens.

The vision system described above has been used as the primary sensor for a mobile robot with good success. The system supplies fast and accurate range data and can generate a floor-plan map of its environment that is used in map-based path planning. During motion of the robotic vehicle, the vision camera is used as a visual proximity detector, by positioning the lens at a fixed focus and monitoring the change in high-frequency content of the scene as the robot travels. A significant rise in this high-frequency information is indicative of a target coming into focus at the range that the lens is imaging. When this condition arises, the robot pauses until it can determine whether or not a collision is imminent. In this application, the 50-mm lens has been most useful. The accuracy of the 105-mm lens is superior, but its field of view (about 11 degrees) is too restrictive.

For three-dimensional imaging tasks, a quick scan of range may be executed to find the gross location of the target. The lens could then be scanned through the target range space at smaller increments, saving the entire video field at each position in a large bit mapped memory. By this method, a three-dimensional representation of the edge-enhanced object could be generated in memory.

The use of optical preprocessing in the swept focus sensor gives it some advantages over other sensing techniques. For example, ranging is accomplished quickly with some other visually based ranging system (such as binocular vision), and tracking of moving objects in the field of view has been demonstrated. There are no "missing part" problems since there is only a single lens, and daily or periodic mechanical alignment is not necessary. The preprocessing action of the short depth of field lens also allows for ranging that is not computation intensive. The system operates in normal ambient light conditions (passively) and responds well to all target objects except those which present a flat field, such as newly painted walls with no visible texture or markings. Determining the dimensions of an object along three orthogonal axes has been demonstrated, and the system has the capability to collect and store three-dimensional image information, for applications which require the manipulation or processing of the entire three-dimensional image. For these reasons, the swept focus vision system makes an excellent primary sensor for mobile robot applications; however, the addition of redundant sensors, (such as ultrasonic) is recommended to ensure the detection of objects which are out of the camera's field of view at close range.

Points of Contact

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Associates and Ferren
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(516) 537-7800

Ali Farsaie
Naval Surface Weapons Center
Code G-45
Silver Spring, Maryland 20910
(202) 394-3850

3.2.7 ERIM Multispectral ALV Sensor

The Environmental Research Institute of Michigan (ERIM) is now developing an advanced ALV ranging device known as the Multispectral ALV (MS-ALV) sensor, intended to provide the same navigation and collision avoidance capabilities of the earlier devices used in the ASV and ALV programs. The operational environment, however, will be rugged cross-country terrain as opposed to the relatively uniform road surfaces used in the initial tests of the Autonomous Land Vehicle concept. The variations in terrain, surface cover, and vegetation encountered in off-road scenarios require an effective means to distinguish between earth, rocks, grass, trees, water, and other natural features.

During preliminary investigation, ERIM conducted an in-depth analysis of these features to ascertain their optimum detection bandwidth frequencies. It was determined, for example, that wavelengths of between 0.52 to 0.55 micrometers are useful in observing the green reflectance peak of the general terrain, in analyzing the soil composition, and in determining water depth. On the other hand, wavelengths of between 2.0 to 2.35 micrometers are well suited for determining the types of vegetation present and the moisture content of the soil. Evaluation of the findings determined that a sensor which could transmit and receive a multispectral signal composed of six different wavelengths should satisfy the requirements for cross-country navigation. The selected wavelengths are 0.53, 0.63, 0.82, 1.06, 1.53, and 2.29 micrometers (reference 49).

Following the terrain analysis, work began to design and develop actual hardware capable of emitting and detecting at these wavelengths. The resulting transmitter consists of two laser sources and a series of bandwidth separating, collimating, and beamsplitting optics. The principle lasing device is a Nd:YAG laser which produces a primary signal at 1.06 micrometers. By frequency doubling this source, the wavelength, is effectively halved creating the 0.53 micrometer signal. By passing both of these transmissions through Raman capillary tube fibers, the wavelengths of 0.63, 1.53, and 2.29 micrometers are produced. (Raman fibers are optical conduits which scatter a portion of the photon energy from the incident laser light resulting in a frequency reduction (i.e., wavelength increase) for the dispersed energy. The scattering is the result of collisions between the incoming laser photons and the molecules which make up the fiber.) The final sensing band, 0.82 micrometer, is supplied by the second lasing source, a gallium aluminum arsenide (GaAlAs) laser diode. All of the signals are combined by dichroic mirrors and other optics to form a single continuous transmission waveform composed of six time-synchronous wavelengths.

Once emitted, the multispectral beam is passed through beam expansion optics to produce the desired rectangular footprint, and then sent to the scanning mechanism. The scanner for the MS-ALV is essentially identical to the scanners developed for the earlier ASV and ALV sensors. The only significant difference is the substitution of a hexagonal rotating mirror instead of a square mirror for panning the beam in azimuth. This configuration causes the transmitted and returned signals to impinge on separate mirrored surfaces, resulting in reduced crosstalk and simplified sensor alignment (figure 27). The nodding mirror which tilts the beam in elevation remains largely unchanged.

The receiver for the MS-ALV sensor presents a special problem because it must detect the presence of all six transmitted wavelengths in the return signal. To accomplish this, ERIM designed a receiver with six separate photodetectors, each matched to one of the corresponding sources. The reflected energy from the terrain is directed through the scanning optics to the receiver. This rectangular beam encounters a dichroic beamsplitting mirror which separates the 2.29 micrometers band from the signal. This portion of the waveform passes through a narrow band-pass filter matched to the wavelength, then continues through a condensor which forms the beam into a point source for the photodetector. In the case of the

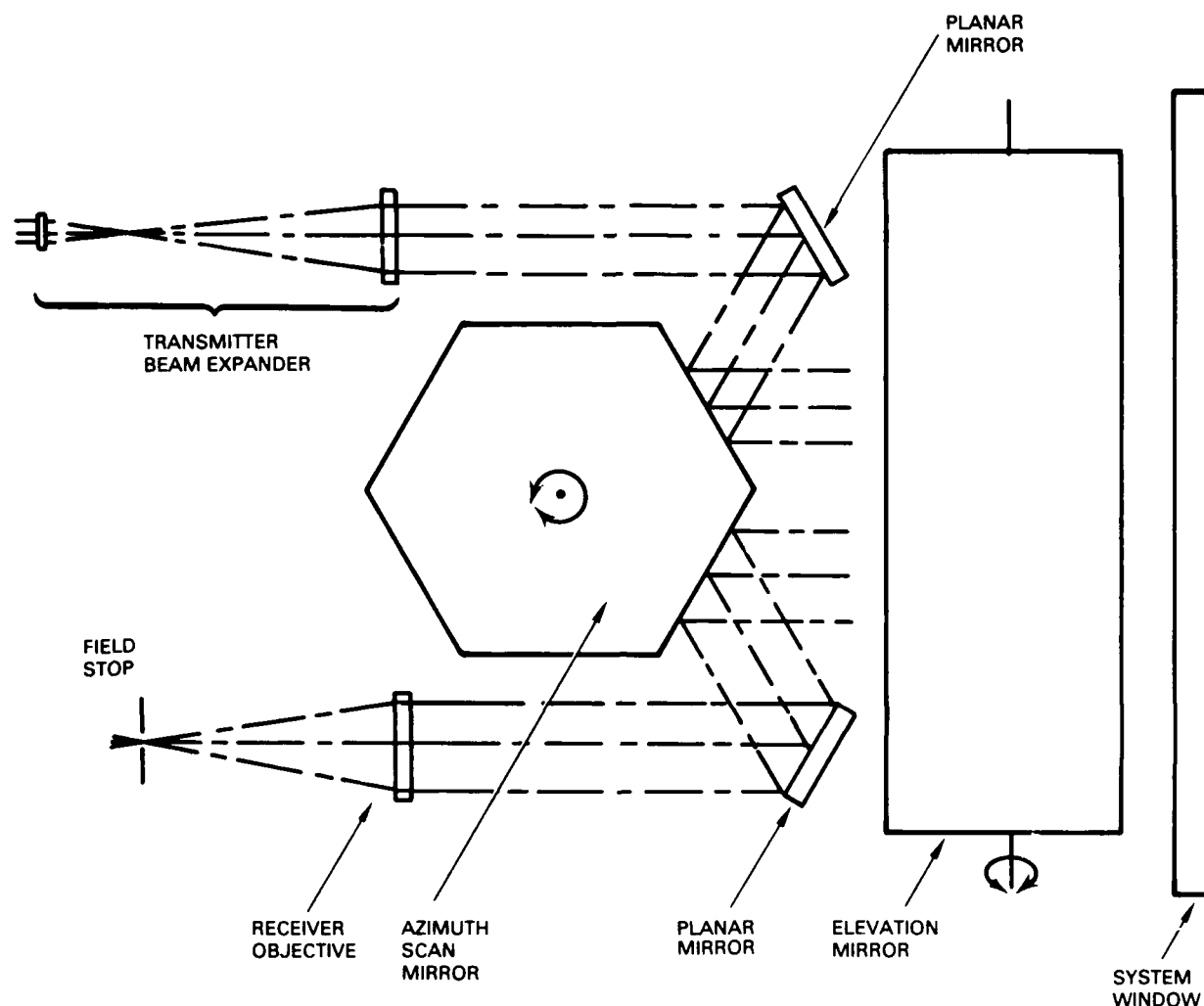


Figure 27. Hexagonal rotating mirror used in the multispectral scanner reduces crosstalk and simplifies mirror alignment. (Courtesy Environmental Resource Institute of Michigan)

2.19-micrometers wavelength, the receiver requires liquid nitrogen cooling because the low transmission intensity of this infrared wavelength results in minimal return radiation. (The extremely cold detector produces a high-contrast surface for the relatively warm beam to strike.) The remaining energy which does not pass the first dichroic mirror is deflected in a cascading fashion to other detectors of similar design. At each receiver the specific wavelength is separated out, condensed, and sent to the respective sensing surface. Figure 28 continues until the final band, 0.53 micrometer, is detected.

Ranging is performed by measuring the phase shift which occurs between the returning continuous wave and a reference beam. The ambiguity interval of the MS-ALV (the distance over which the phase difference remains less than 360 degrees) is 75 feet, which dictates the maximum effective range of the sensor. (Beyond this point the phase pattern repeats, causing uncertainty in the distance measurement.)

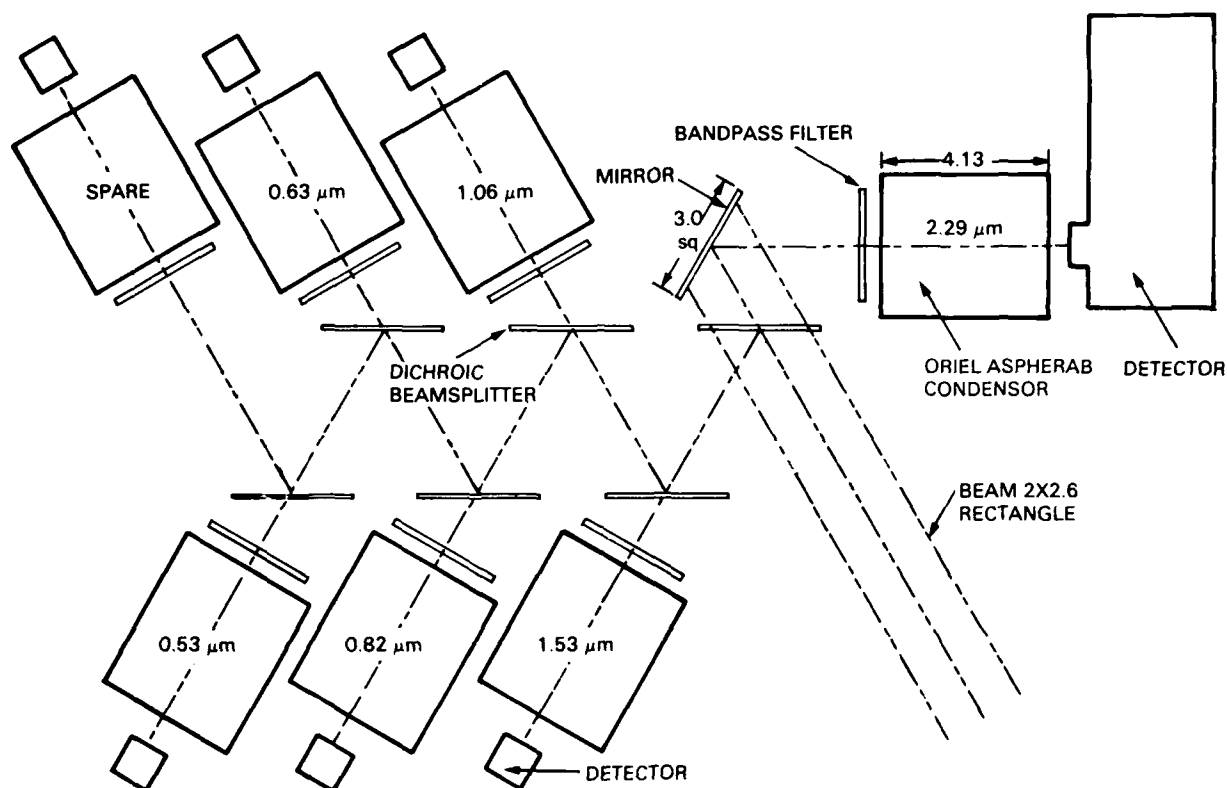


Figure 28. Block Diagram of the multispectral ALV Scanner. (Courtesy ERIM)

The raw data produced are presented as output according to an "angle, angle, attribute" format. The angles correspond to the position and orientation of the scanning mirrors and locate the point being observed within the field of view. The attribute field is a 13-bit word containing a single range value for the site and six reflectance values representing the intensity of each of the laser wavelengths present in the composite beam reflected from that location. The range figure is based on the 1.06 micrometer source because of the strength of its transmission.

The multiple frequency sources, corresponding detectors, detector cooling system, and the scanner result in significant power consumption (15 kilowatts). The mass of the scanning mirrors and mechanism plus the plurality of lasers, optics, and detectors make the multispectral sensor heavy, increasing the complexity of the control and analysis required to produce results. As a result, initial prototypes will have application only on the largest of mobile robotic platforms capable of supporting the size, weight, energy, and computational overhead.

Selected Preliminary Design Specifications

Ranging Technique	Phase Shift Measurement
Field of view	60 degrees (horizontal)
	60 degrees (vertical)
Beamwidth	0.23 degree
Frame Rate	2 frames/second
Scan Rate	640 lines/second
Maximum Range	75 meters
Laser Wavelengths	0.53, 0.63, 0.83, 1.06, 1.53, and 2.29 micrometers
Power Requirements	15 kilowatts
Enclosure	12 x 3 x 2 feet
Weight	600 pounds

Point of Contact

Environmental Research Institute of Michigan
Box 8618
Ann Arbor, Michigan 48107
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3.2.8 RVSI Long Optical Ranging and Detection System (LORDS)

As an outgrowth of research conducted over a 7-year period, Robotic Vision Systems, Inc. has conceptually designed a innovative laser-based ranging system capable of acquiring three-dimensional image data for an entire scene without scanning. The *Long Optical Ranging and Detection System* (LORDS) is a patented concept incorporating an optical encoding technique with ordinary vidicon or solid state camera(s), resulting in precise distance measurement to multiple targets in a scene from a single laser light pulse. Created to provide a ranging capability beyond the typical 12- to 36-inch standoff distances of the company's three-dimensional vision product line. The sensor is designed to operate out to distances between 1 meter and several kilometers. Characteristics such as real-time data acquisition rates, day or night operation, low cost, compact size, and high resolution from low-bandwidth components make LORDS ideally suited to the navigation, guidance, obstacle avoidance, target detection, and identification functions of military and industrial robotic vehicles.

The design configuration is relatively simple and comparable in size and weight to traditional phase shift measurement laser rangefinders (figure 29). Major components include a single laser energy source, one or more imaging cameras each with an electronically implemented shuttering mechanism, and the associated control and processing electronics. In a typical configuration, the laser will emit a 25-millijoule pulse lasting 2 nanoseconds, for an effective transmission of 12.5 megawatts. The anticipated operational wavelength will lie between 432 and 830 nanometers (due to the ready availability within this range of the required laser source and imaging arrays).

The cameras will be two-dimensional charge-coupled device (CCD) arrays spaced closely together side by side, with parallel optical axes resulting in nearly identical, multiple views of the illuminated surface. Lenses for these cameras will be of the standard photographic varieties between 12 and 135 millimeters. The shuttering function will be performed by Microchannel Plate Image Intensifiers (MCPs) 18 or 25 millimeters in size, which will be gated in a binary encoding sequence, effectively turning the CCDs on and off during the detection phase. Control of the system will be handled by a single-board processor based on the Motorola MC-68010.

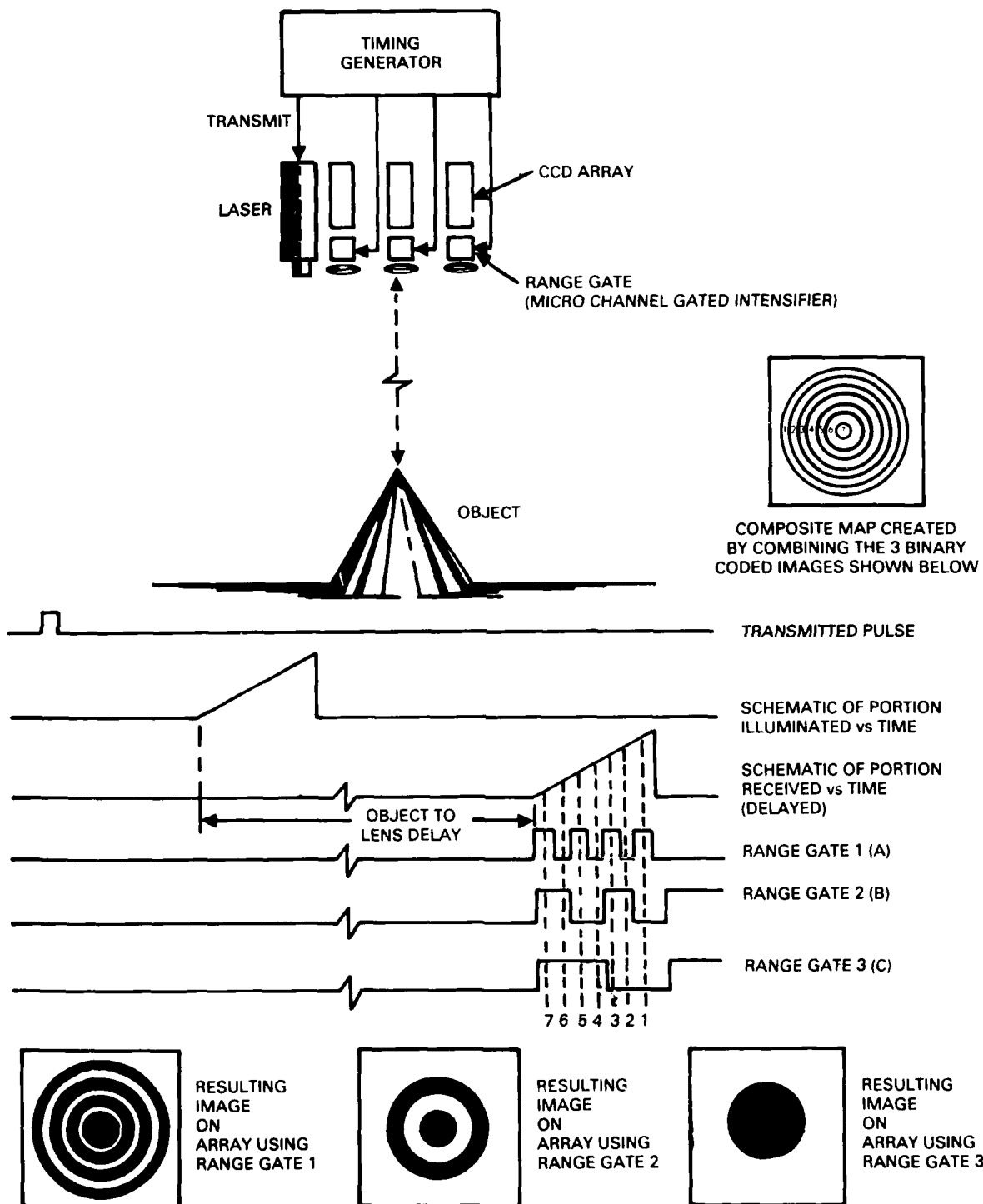


Figure 29. Block diagram of the RVSI LORDS ranging concept. (Courtesy RVSI)

LORDS obtains three-dimensional image information in real time by employing a novel time-of-flight technique requiring only a single laser pulse to collect all the information for an entire scene. The emitted pulse journeys a finite distance over time; hence, light traveling for 2 milliseconds will illuminate a scene a greater distance away than light traveling only 1 millisecond. An alternate way to state this is that at any given time the light will define a two-dimensional image surface a set distance from the sensor.

LORDS divides its entire sensing range into discrete distance increments each representing a distinct range plane. This sensing is accomplished by simultaneously gating the MCPs of the observation cameras according to their own unique, binary (on off) encoding pattern over the duration of the detection phase, alternately blocking and passing any return signal resulting from the reflection of the laser emission off of objects within the scene. As a result, when the gating cycles of each camera are lined up and compared there exists a uniquely coded correspondence which can be used to calculate the range to any pixel in the scene.

For instance, in a system configured with only one camera, the gating MCP would be cycled on for half the detection duration, then off the remainder of the time. Figure 29 shows any object detected by this camera must be positioned within the first half of the sensor's overall range (half the distance the laser light could travel in the allotted detection time). However, significant distance ambiguity exists because the exact time of detection of reflected energy could have occurred anywhere within this relatively long interval.

This ambiguity can be reduced by a factor of two through the use of a second camera. Its associated gating is cycled at twice the rate of the first, thereby creating two complete on-off sequences, one taking place while the first camera is on and the other while the first camera is off. Simple binary logic can be used to combine the camera outputs and further resolve the range. If the first camera did not detect an object but the second detector did, then by examining the instance when the first camera is off and the second is on, the range to the object can be associated with a relatively specific time frame.

Incorporating a third camera at twice the gating frequency (two cycles for every one of Camera 2 and four cycles for every one of Camera 1) provides even more resolution. Following the same logic as before, if the object in the above example is also seen by the third detector the unique occurrence of the pattern "off-on-on" for the first, second, and third cameras respectively pinpoints precisely the range. Notice that for a three camera arrangement there are eight nonrepeatable detection combinations, which means the sensing range is divided into eight intervals. For each additional CCD array incorporated into the system, the number of distance divisions is effectively doubled, resulting in significant improvements in resolution over the specified range.

Alternatively, the same encoding effect can be achieved using a single camera when little or no relative motion exists between the sensor and the target area. In this scenario, the laser is pulsed multiple times, and the gating frequency for the single camera is sequentially changed at each new transmission. This effectively creates the same detection intervals as before, but with an increase in the time required for data acquisition. A combination of both methods is also possible. This modularity allows for system customizing to meet the needs of the specific application.

An important characteristic of LORDS is its ability to range over selective segments of an observed scene. This feature can be used to advantage to improve resolution. The distance over which a given number of range increments is spread can be variable. Initially, the entire range of interest may be observed, resulting in the maximum distance between increments (coarse resolution). An object detected at this stage can thus be localized to a specific, abbreviated region of the total area. The sensor is then electronically reconfigured to cycle only over this region, which significantly shortens the distance between increments, thereby increasing resolution. This is done by providing a known delay between transmission and the time when detection/gating process is initiated; the sensor allows the light to travel to the region of interest without concern for objects positioned in the foreground.

Point of Contact

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3.2.9 TOSC Passive Ranging Using Scene Information

The Optical Sciences Company, Placentia, California, is developing imaging sensor technology capable of providing range data to all points in the scene being viewed. Two approaches to the realization of this ranging capability are under study, one appropriate for use from stationary as well as moving platforms, and the other restricted to use on moving platforms only. Both approaches are based on a unique, quite sophisticated, and yet easy to implement image processing algorithm which allows comparable portions of two images of the same scene to be compared to determine the misregistration (image displacement) between the two images. This algorithm, referred to as IDEA (image displacement estimation algorithm) provides displacement estimates with a precision of a few millipixels.

In the first approach to ranging, IDEA is used to process image data as gathered by a camera alternately viewing through the two ports of a stereo rangefinder; range estimates can be generated automatically for all regions in the camera's field of view. The remarkable precision of IDEA allows range estimates to be generated for targets at many kilometers distance, even with a rather small stereo baseline. TOSC is currently under contract to the Naval Ocean Systems Center, San Diego, to develop a laboratory demonstration prototype for the Marine Corps. This system will have a 1-meter baseline separation, and is intended to range targets from 100 meters to 10 kilometers away, with an accuracy of 3 percent at full range.

The second approach, intended for use on a moving platform, is based on the presumed knowledge of vehicle velocity. An ordinary imaging sensor views the scene in the direction of travel; as the platform moves forward, objects in the scene are observed to move outward towards the edge of the field of view. *IDEA is used to provide an estimate of the rate at which adjacent areas of the scene are moving apart*, which when combined with platform velocity yields a quite accurate estimate of range to any region within the field of view. With this approach, the range to nearby targets can easily be estimated with a precision adequate for land navigation and collision avoidance. Additionally, the company feels that range estimations to distant objects will be sufficiently accurate to support most fire control/targeting requirements, as well as terrain following/avoidance flight control of aircraft.

Point of Contact

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3.2.10 Digital Signal Laser Radar Sensor

An advanced laser radar sensor being developed by Digital Signal Corporation to precisely measure distances to as close as 0.0001 inch has potential application to three-dimensional vision for robotic platforms. The proposed system incorporates a continuous wave, frequency modulated injection laser diode with fiber optic scanning for ease of system implementation (reference 50). The device is capable of performing continuous, high resolution (0.1 mil) ranging to machined metal or composite surfaces at distances of meters, at scan rates of 1000 pixels per second. Initial applications include contour mapping, noncontact gaging, and surface quality determination.

This accuracy is inherent to the extremely wide frequency tuning range of the injection laser (section 2.1.5). The scanner for the Laser Radar Sensor is composed of a General Scanning GF-220D optical system for tilting the transmission beam in elevation and a Lincoln Lasers spinning facet wheel with 24 surfaces for panning the source in azimuth.

For three-dimensional vision applications associated with mobile robotic platforms, the sensor can be configured as a high frame rate mapper capable of real-time operations. To achieve real-time rates, the time spent per pixel (pixel dwell time) must be reduced to submicrosecond values. As a consequence the accuracy of the radar system diminishes; however, the decrease is not excessive and the precision remains reasonable. By applying signal processing techniques to the mapping sequence, resolutions approaching 0.1 inch are possible at dwell times of approximately 5 microseconds per pixel. This translates to a scan rate of 5 megapixels per second; range picture frame rates for a 256 by 256 pixel field of view scene can reach 100 frames per second.

Point of Contact

Digital Signal Corporation
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Springfield, Virginia 22151
(703) 321-4910

3.2.11 Optima Portable Laser Ranging System

Optima Systems, Inc. has developed a laser-based remote distance measurement technique originally intended for short range (under 50 feet) and high accuracy (a hundredth of an inch). The system can be modified for applications requiring greater range capabilities and/or less stringent accuracy requirements. A few of the possible applications of the system include automated assembly, inspection, land surveying, robotic ranging, collision avoidance, alignment and assembly of large structures, and the measurement of fluid height in large storage tanks.

Range is determined through phase shift measurement; an amplitude modulated laser is directed at the target object, and the modulated beam is partially reflected back to the system. This method of measurement is well suited to robotic ranging since it does not require the use of a special retroreflective target. Due to the time of flight required for the beam to travel to and from the target, the phase of the returning beam differs proportionally with the target distance. Optima has developed a proprietary method which employs advanced signal processing techniques to accurately determine the phase difference.

A laboratory prototype model which displays the principles of operation has been assembled. This prototype is about 2 feet long, 1 foot wide, half a foot high, and weighs under 20 pounds, and is interfaced to an IBM PC which performs calculations and displays the measurements. Actual production models could be made one-fifth the size and weight (4 pounds) of the prototype. The IBM PC could be replaced with an onboard microprocessor for field models. In production quantities, the price of this unit is estimated to be \$2,000.

To form a robotic collision avoidance system, it would be possible to integrate several of the range measurement sensors and have each provide distance and bearing information by scanning the environment of the robot. A typical sensor could be designed to have a range of over 100 feet with an accuracy on the order of an inch. Accuracy could be increased automatically for objects that are closer. The collimated laser beam of each sensor could be focused onto small target areas to provide precise range measurements in complex surroundings with multiple targets.

Point of Contact

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Optima Systems, Inc.
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3.2.12 Honeywell Displaced Sensor Ranging Unit

Honeywell Visitrone has developed prototype versions of a ranging system using a near-infrared LED source and displaced silicon detectors to provide ranging from one-half to 2 meters with resolution of 6 millimeters at 1 meter and response of less than 5 milliseconds. This prototype is packaged in an enclosure 51 by 51 by 150 millimeters long with a weight of 0.65 kilogram.

The system determines range through measurement of return signal intensity (section 2.1.8). The basic approach is to project a momentary pulse of infrared radiation onto the surface to be measured and to detect the reflected flux with two sensors which are displaced along the measurement axis. The signal from each sensor may be represented by

$$\text{SIGNAL 1} \propto \frac{(\text{PROJECTED SPOT FLUX}) * (\text{SURFACE REFLECTIVITY})}{(\text{RANGE})^2}$$

$$\text{SIGNAL 1} \propto \frac{(\text{PROJECTED SPOT FLUX}) * (\text{SURFACE REFLECTIVITY})}{(\text{RANGE} + \text{DISPLACEMENT})^2}$$

The detected signals thus provide a means to determine the range independent of the surface reflectivity. The use of twin displaced detectors as opposed to two displaced emitters offers the advantage of matched stable response and excellent linearity. LED emitters are temperature sensitive and have an output which will change with age thus making it difficult to maintain identical output.

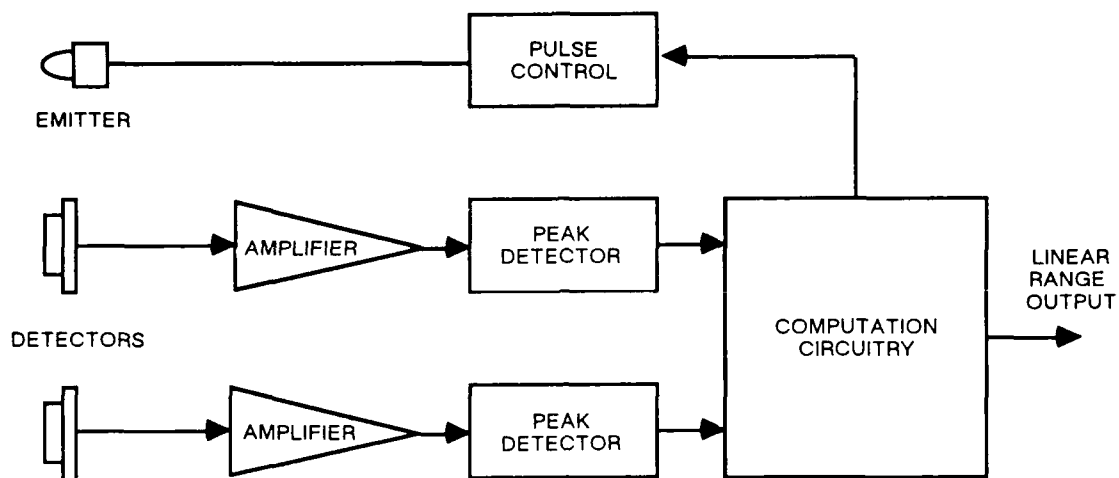


Figure 30. The optical system is designed to provide a field of view of about 7 degrees and to provide an adequate return signal at ranges out to 2 meters even with surfaces with poor reflectivity.

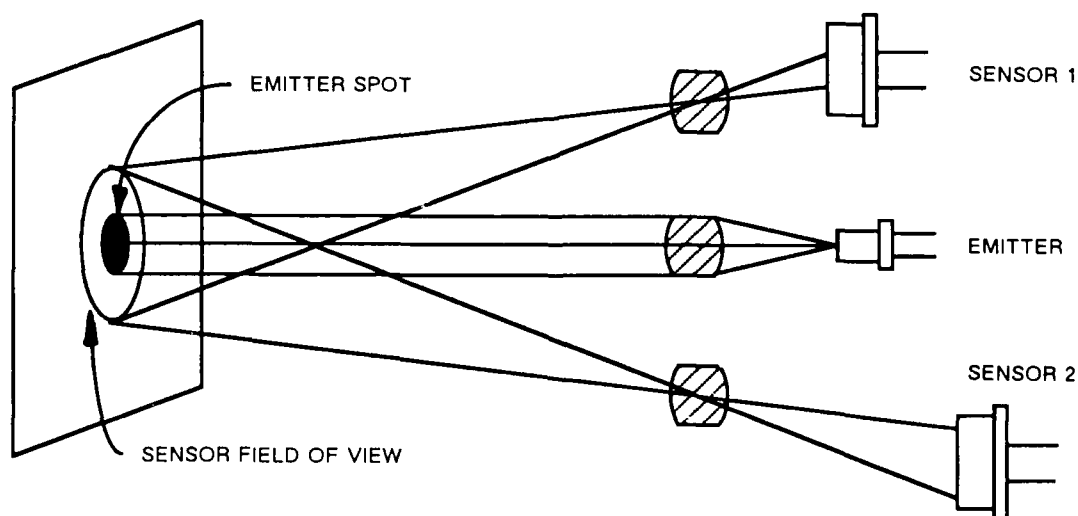


Figure 31. Block diagram of the Honeywell displaced sensor ranging system.

Computation of range can be achieved in a variety of ways and an output provided which is linear with range. The system in the current prototype provides a source pulse repetition frequency which is proportional to range and gives linear output and enhanced performance at maximum distances.

The performance which has been achieved at Honeywell with the prototype system is summarized below:

Range	0.5 to 2 meters
Resolution	2.5 to 34 millimeters
Response (10% to 90%)	5 meters
Output	0 to 5 volts linear with range
Field Of View	7 degrees
Ambient Illumination To	100,000 lux sunlight
	5,000 lux tungsten
Targets	>30% nonspecular reflectivity

One characteristic of active systems is that when a specular surface (mirror-like reflection) is viewed along a normal to the surface, anomalous range information results. This condition does not occur frequently and is avoided if the sensor is inclined a few degrees or more from the surface normal. The prototype illustrates some of the advantages of using the displaced sensors measurement technique. The system is very rugged and foolproof since no moving parts are required and is packaged in a relatively small volume. The prototype uses standard off the shelf components. A light emitting diode is used rather than a laser source which further simplifies the system and reduces the safety related concerns.

Point of Contact

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Englewood, Colorado 80155
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3.2.13 Optima Hand-Held Microwave Ranging System

Optima Systems, Inc. is currently working on the prototype of a hand-held microwave ranging system. This system is capable of measuring the range and relative velocity of a remote target anywhere from 10 to 500 feet away. Currently obtained range accuracy is approximately 10 percent, and velocity is accurate to within +/- 1 mph from 0- to 50-mph differential velocity.

The system uses a microwave carrier frequency of 24.125 GHz tied to a 10-kHz sine wave. This signal sent toward a remote target and received back by the microwave detector. This reflected signal is both phase and frequency shifted from the original signal. The phase shift of the modulated signal is proportional to the target distance while the frequency (Doppler) shift is proportional to the relative speed between the system and target. This signal is passed through two separate filters, one which extracts range information and the other which extracts velocity information. A microprocessor is used to read the range and velocity information, perform appropriate unit conversion calculations, and display the results on a LED readout.

Point of Contact

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3.2.14 Battelle Steerable-Beam Millimeter Wave Radar

Researchers at the Battelle Memorial Institute have developed a beam-steerable millimeter-wave antenna for use on an automobile collision-avoidance radar system. The new antenna can provide azimuth information in addition to distance data for any objects in the car's path. Battelle is hoping to interest automotive companies in licensing the new antenna, or becoming investment partners in the development of a collision-avoidance system, projecting that costs could be driven down quickly to a few hundred dollars (reference 51).

The radar is a frequency modulated continuous wave (FM/CW) system coupled with a beam-steerable antenna. The center frequency is at or near 50 GHz (6-millimeter wavelength). This type of radar allows range, velocity, relative amplitude (size or radar cross section), and angle determination for multiple targets. The 50 GHz frequency requires a relatively small antenna. At this frequency, long-range propagation of interfering signals is reduced due to atmospheric oxygen absorption. The basic radar would be capable of monitoring out to a range of over 3 kilometers without range ambiguities. However, returns from targets at ranges exceeding 100 meters will be filtered so that they will not interfere with signals for the targets of interest.

The 50-GHz source generates a linear frequency modulated signal with a total change in frequency of 30 MHz (this bandwidth is required to obtain a 5-meter range resolution). The 50-GHz signal is used as the source for the transmit/receive antenna and for the local oscillator for the two mixers. The transmitted signal is reflected from targets of interest and is received by the same transmit/receive antenna. The received signal is mixed with the local oscillator output, generating a difference or intermediate frequency (IF). The amplitude of the IF is proportional to the size of the target (range to the target must be considered), while the frequency is proportional to the distance between the antenna and the target.

There are two IF outputs from the RF section, which are in quadrature. These signals are required to generate the range and velocity data. Each IF signal is band-limited to the frequency range of 40 to 845 kHz. This frequency range corresponds to the IF for a target in the range of 5 to 100 meters. The output from this equalizing filter is then applied to a bank of sixteen individual bandpass filters (reference 52). The output from each filter corresponds to a signal from a given range bin as follows:

5 to 60 meters -- 5 meter range bin

60 to 100 meters -- 10 meter range bin

This results in a range resolution of 5 meters when a target is within 60 meters of the antenna, and a resolution of 10 meters when a target is within 60 to 100 meters of the antenna.

A frequency counter is used to count the number of zero crossings of the IF signal for a given range filter. The counter determines the actual frequency of the IF signal and, therefore, the range to the target. The outputs from the 16 filters for both IF channels are multiplexed and then converted to a digital format by an 8-bit A/D converter. The data from the A/D converter are passed to a computer for further processing (reference 52).

The system controller provides an analog control signal to the 50-GHz solid state source. The analog control signal is used to generate the linear frequency modulated sweep over the 30 MHz bandwidth. This sweep is accomplished every 24 microseconds. The controller also serves as the interface to the beam-steerable antenna, monitoring the beam position as a function of time. This interface is required to insure that the radar knows where the antenna is pointing. The antenna must dwell at a particular look angle for a 3 milliseconds to obtain the desired velocity accuracy. During the 3-milliseconds time period the source generates 128 FM sweeps.

The proposed antenna would use a Battelle "diffraction electronics" concept (reference 53) for a mechanically steered beam which covers ± 15 degrees azimuth range, yielding a coverage of ± 25 meters from centerline at the 100 meter range. The beamwidth will vary from 1 degree at the straight ahead or 0 degree position to 4 degrees at the ± 15 degree positions. The scan will be a sawtooth scan with a 0.006-second dwell at each of 15 beam positions. Figure 30 illustrates the antenna will be implemented by patterning a rotating drum. The 2-inch diameter drum will rotate at a constant speed of 666 RPM. The beam will be scanned horizontally by using different periodic grating spacings around the drum circumference. The beamwidth will be varied during the scan by using a novel technique developed at Battelle.

A vertical beamwidth of 3 degrees will be obtained through use of a cylindrical reflector. The reflector will be nominally 4-1/2 inches high to provide a 3-degree vertical beam at 50 GHz. The scan rate can be controlled by sensing an index mark on the drum which, combined with a speed control, will maintain a constant rotation rate. The entire antenna structure including the waveguide feed, the diffraction drum, and the reflector will be located behind the dielectric panel which will function as a protective radome.

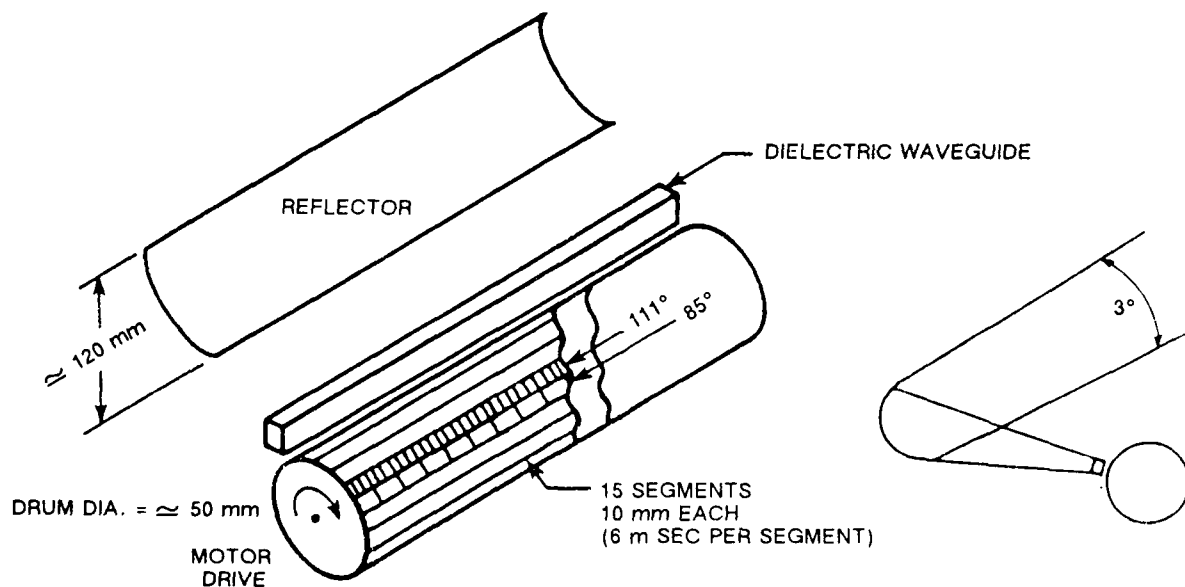


Figure 32. A rotating drum forms the heart of the Battelle diffraction antenna beam steering concept. (Courtesy Battelle Columbus)

Selected Specifications

Antenna	Mechanically scanned over a total of 30 degrees.
Antenna Pattern	Three degrees beamwidth in elevation Variable 1 to 4 degrees in azimuth.
Operational Frequency	Nominally 50 GHz
Range Resolution	5 meters resolution from 5 to 60 meters 10 meters resolution from 60 to 100 meters
Maximum Ranges	Unambiguously handle targets to 3 kilometers
Range Accuracy	Estimated to be less than 1 meter for the close ranges (roughly from 5 to 20 meters).
Velocity Accuracy	One m/3 for closing velocities of 1 m/s to 63 m/3.
Response Time	Single scan every 0.2 second.

Point of Contact

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3.3 INTERESTING RESEARCH

3.3.1 Ultrasonic Scanning System

This ultrasonic ranging system, developed at Taiwan University and intended for installation on an intelligent mobile robot, employs a combination of time of flight and triangulation techniques for the detection and location of moving objects (reference 54). The sensor consists of an array of four ultrasonic transceivers arranged in a square pattern, which detect in pairs for measurement redundancy and improved reliability (Figure 31). Range is determined by time-of-flight sensing for each of the active transducers in the pair, whereupon the position of the object is determined by triangulation.

Detection capability is improved through the use of multifrequency transmissions obtained by selectively firing one of four transceiver drivers, each operating at a different frequency. The activation sequence is provided by a microprocessor controlled multiplexer. This capability takes advantage of the long range qualities of the lower frequencies and the directional and resolution qualities of the higher frequencies. The term "scanning" refers to the dispersion of the ultrasonic energy over a wide field of view and to the added coverage afforded by multiple transducers, not to any electrical or mechanical slewing of the device.

Limitations of the present prototype include the occurrence of dead sensing spots due to the physical separation of the transducers (figure 33), and the narrow coverage area. Also, there are problems in detecting multiple objects, because the control circuitry only accepts the first return echo.

3.3.2 HILARE

Work being performed at the Laboratoire d'Automatique et d'Analyse des Systemes in Toulouse, France, involves the development of a navigation subsystem for the mobile robot HILARE based on ultrasonic rangefinders and near-infrared proximity detectors (reference 55). This research is part of a larger effort in the design and production of multisensor and multilevel decision systems for autonomous mobile robots.

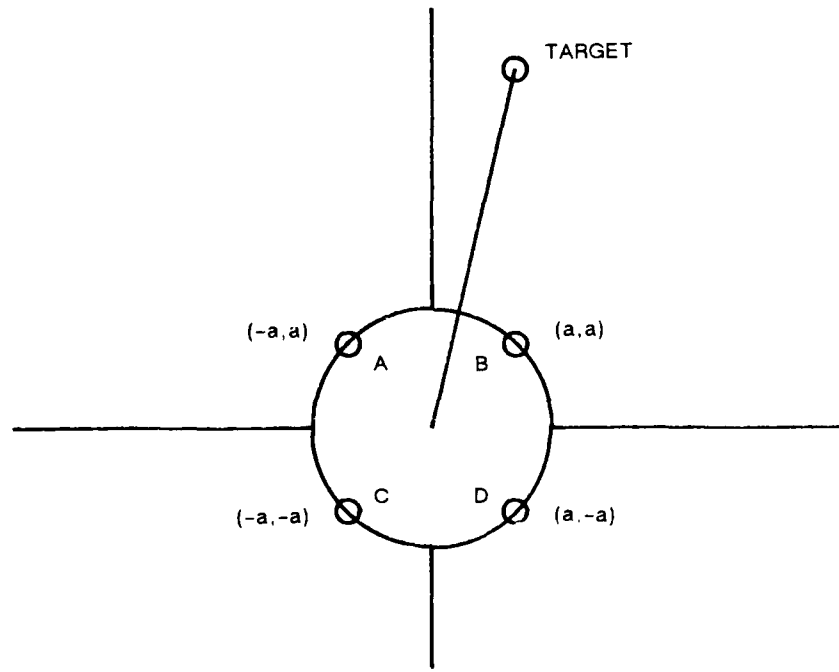


Figure 33. Target position is more precisely determined through a combination of TOF ranging and triangulation using an array of four transducers (reference 54).

The tracking subsystem of the HILARE robot used for determining vehicle position and orientation consists of two near-infrared emitter detectors mounted 25 centimeters apart on a rotating vertical mast, used in conjunction with reflective beacons at known locations in three corners of the room. Figure 34A shows each of the three beacons in turn are constructed of retroreflective tape applied to three vertical cylinders spaced in a recognizable configuration 25 centimeters apart. One of the beacon configurations is inverted so as to be distinguishable from the others, for purposes of establishing an origin. The cylinders are vertically spaced to intersect the two planes generated by the rotating optical axes of the two emitter-receivers on the robot. A detected reflection pattern such as shown in figure 32B confirms beacon acquisition. Angular position is inferred from the stepper motor commands which drive the scanning mechanism.

Ultrasonic transducers are employed for close-in obstacle avoidance and specialized navigation without using vision. (Specialized navigation includes traversing corridors, moving along walls, and circumventing obstacles.) The ultrasonic ranging subsystem uses 14 Philip EFR RSP 36K21 transceivers operating at 36 kHz with a 30-degree transmission dispersion. The transducers determine range by time-of-flight methods, and can measure distances of about 2 meters with an accuracy of 0.5 centimeter.

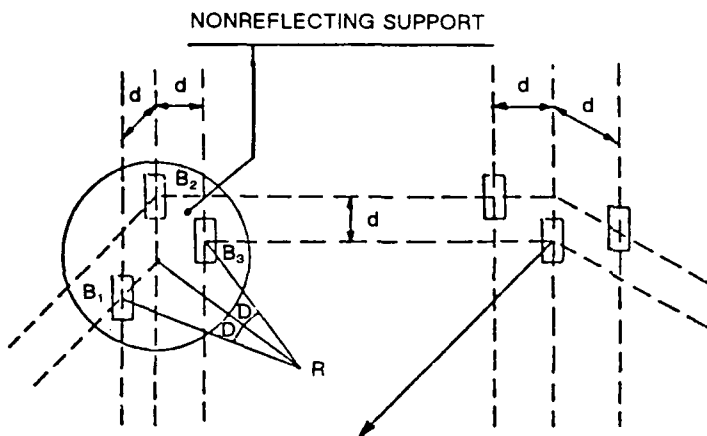


Figure 34A. Vertical retroreflective cylinders used for navigation (reference 55).

NONREJECTED CASE

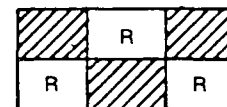


Figure 34B. Detected reflection pattern confirms acquisition.

3.3.3 Ultrasonics for Object Recognition

A high resolution time-of-flight ultrasonic rangefinding system has been developed at the Robotics Research Laboratory of the University of California, Davis, to overcome the limitations of grey scale imaging techniques in object recognition (reference 56). The sensor consists of two ultrasonic transducers spaced close together on a platform capable of moving in three dimensions. One transducer transmits a highly directional 215-kHz narrow beam (10-degree beam angle) acoustic pulse, while the other transducer detects the returning echo. The system is capable of 100 pulses per second with a resolution of ± 0.001 inch, but has a maximum range of only 2 feet due to attenuation of the high-frequency beam in air.

Object recognition occurs in two steps. The learning phase takes the range data acquired from known objects, creates a descriptive model of the objects, and stores the models for later use. The recognition phase involves observing objects in an unknown environment, obtaining range data points for the objects, and matching the resulting object descriptions to the stored models. Matching is region-based.

3.3.4 Ultrasonic Phased Array Rangefinder

Research at the Massachusetts Institute of Technology has resulted in the design of a prototype multitransducer ultrasonic ranging sensor with improved angular resolution (reference 57). The device arranges four Polaroid transducers in a linear array spaced 1 inch apart and operating at a frequency of 50 kHz. By firing the transceivers in sequence with a uniform delay period, the additive and/or subtractive properties of the overlapping transmissions combine to form a highly directional beam with an adjustable dispersion angle. This phased array sensor has a minimum effective range of 4.4 feet, below which the interelement phasing becomes increasingly harder to implement until the advantages of the array no longer surpass the capabilities of a single transducer.

The research discussion does not mention a specific maximum range for the sensor; however, the four-transducer system is compared to a previously developed device with eight transducers which can range to 75 feet. The beamwidth (and angular resolution) can be electronically adjusted to suit the application requirements.

3.3.5 Multimodal Generic Robot Sensor

Experimental development of a generic robotic sensor package is taking place at Martin Marietta Denver Aerospace. Constructed of commercially available components, the system consists of a GE TN 2500 video camera with a flash illuminator, a Lietz Red Mini laser rangefinder, and four Polaroid ultrasonic rangefinders (reference 18).

Proper functioning of the sensor requires that retroreflectors be placed on the objects being observed. The effective operating range of the unit is between 0.1 and 30 meters. Applications of the device include robotic cargo handling, refueling, and vehicle conveying. Operation of this multimodal sensor begins with camera observation of an object, such as a cargo crate, with a prearranged pattern of retroreflectors mounted on it. The retroreflectors are illuminated by the flashing light source, and the resulting camera image is used to determine the relative orientation of the object. A more advanced vision system would find critical features (vertices, edges, and regions) without the help of target markings, but much of the processing thereafter would be similar (reference 59). (It is felt that advances in vision systems in the near future will include the development of custom designed, possibly parallel, processors that can perform this "front end" scene analysis, extracting image primitives in real time.) The laser rangefinder is used for accurate range measurement from 1 to 30 meters, while the ultrasonics are used for close-in ranging of less than 1 meter.

Point of Contact

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3.3.6 Ground Vehicle Automatic Guidance System

An interesting application of laser rangefinding being pursued in Japan involves the automation of the world's highways. A prototype automatic lateral control system for automobiles is under development to handle the problem of keeping a vehicle at a predetermined position and direction within a traffic lane of a roadway. The combination time-of-flight/triangulation sensor incorporates a scanning laser detector system attached to the vehicle as an active sensing source, and corner-cube prisms distributed along the roadside as a passive reference system (reference 60).

The scanner, which produces a fan-shaped laser plane, pans the plane forward and back and tilts the elevation of the plane in search of the corner-cube reference points. When the laser plane encounters a cube, the beam is reflected back to a photodetector for detection and time-of-flight processing. Once detected, the pan and tilt angles are measured. By detecting and measuring between two reference points, the lateral position and direction of a vehicle relative to a desired path can be calculated (figure 35). The panning motion provides a forward-looking capability important to negotiating curves and other changes in the roadway. The scanner uses a 5-mW He-Ne laser with a 20-degree dispersion angle. The scanning frequency is 30 Hz, with an angular resolution of 0.15 degree. Position and direction can be determined every half cycle of the plane scan.

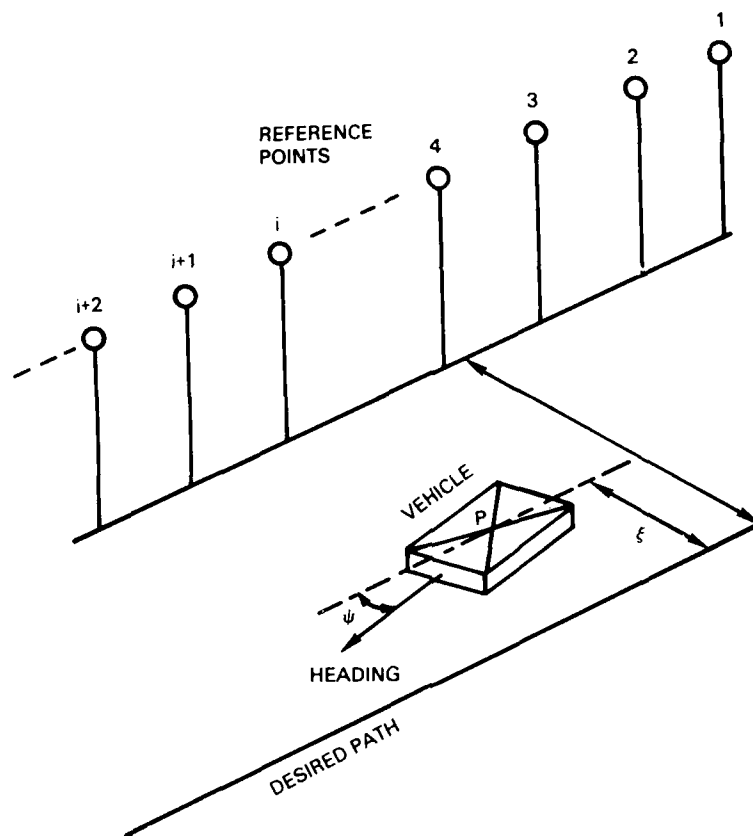


Figure 35. Retroreflectors placed alongside a roadway are used as references in a proposed automatic lateral positioning scheme (reference 60).

3.3.7 Vehicle Location by Laser Rangefinding

A development out of the Institut National des Sciences Appliquées, Codex, France, uses an active triangulation scanning laser rangefinder to determine the position and orientation of a mobile robot in an a priori environment. Location is determined by detecting edges of cylindrical polyhedral obstacles, then matching their positions with a known model of the environment.

The first step in this process involves the creation of a visibility map for the specific environment. From this the general location of the vehicle is calculated by counting the number of edges seen by the robot from its current position. This scheme is based on the assumption that from any given position in a known world only a portion of the total points or object vertices can be viewed. Once the rough location of the robot is determined the absolute position is calculated from direct measurement to the observed vertices by the rangefinder. Ranging is accomplished through simple triangulation, using a 10-mW He-Ne laser mounted on a microprocessor-controlled scanning platform. Detection of the reflected beam is performed by a single linear CCD array Reticon camera with 1024 elements.

3.3.8 NOSC Vision and Ranging Module

The Autonomous Systems Group at the Naval Ocean Systems Center (NOSC) is developing an integrated video and laser ranging module for the Ground Surveillance Robot project funded by the U.S. Marine Corps. The M114 tracked vehicle used in this effort is a general robotics testbed to which multiple sensor subsystems are attached (figure 36).

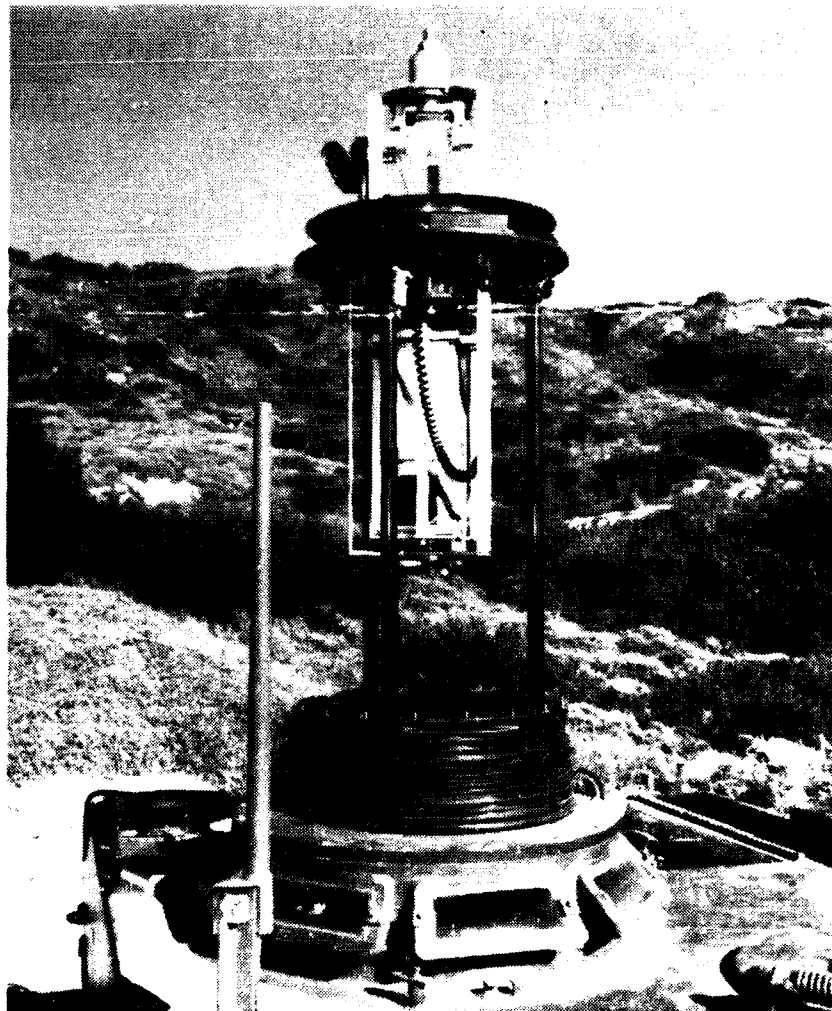


Figure 36. NOSC Vision and Ranging Module mounted on the USMC Ground Surveillance Robot.

The mechanical structure of the sensor platform consists of an electric leadscrew-actuated lift which can extend an instrument package up to 2 meters above the vehicle (figure 37). Atop this, a rotary table provides a common azimuth axis for cameras and a high power, high slew rate laser-fire directing mirror. The mirror has its own independent pitch and yaw axes, allowing the directed laser beam to explore a region ± 30 degrees in azimuth and ± 50 degrees in elevation. (This is relative to the common azimuth axis shared with the primary video camera, which also has independent pitch and roll axes.) All six axes are computer-controlled closed-loop servo systems, with 14-bit accurate absolute positioning (can be upgraded to 16-bit accuracy).

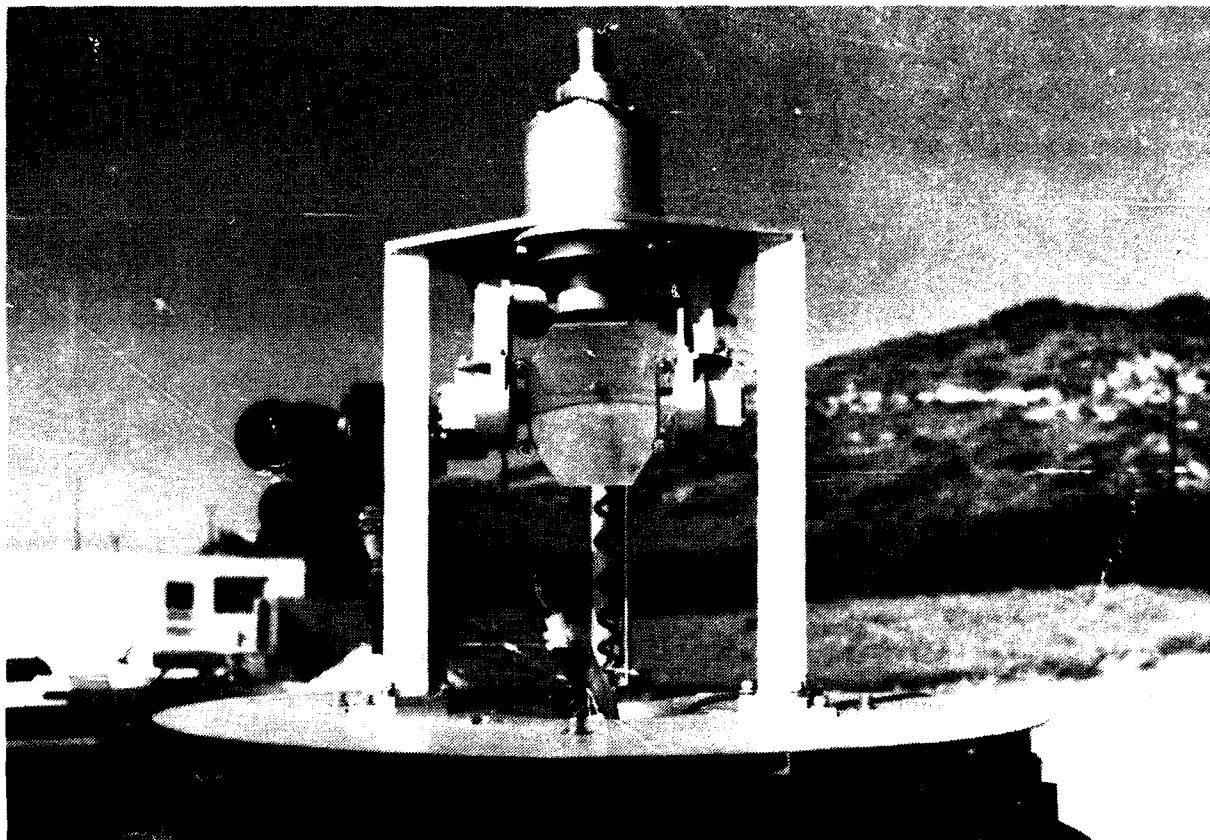


Figure 37. Close-up of laser directing mirror on the NOSC Vision and Ranging Module.

The primary camera is a 512-by 490-pixel gray scale unit equipped with computer-controlled auto-iris and a motorized zoom lens. The unit was obtained without the standard infrared filter, allowing the CCD array to respond to 1.06-micron radiation. The laser ranging system is the Laser Photonics YQF 113 (see section 3.1.8). The detector unit has been incorporated into the transmitter case, reducing the optical axis displacements to 50 millimeters. This allows a single steered mirror to both direct the outgoing beam as well as reflect incoming radiation to the detector. The entire system allows roll, pitch, yaw, elevation, and field-of-view control of the camera scene, as well as independent pan and tilt laser ranging search of the imaged area at a 30-Hz rate. Sensor platform control, which includes all motion axes, video image acquisition, and laser firing, may be manually initiated, electronic, or programmed.

Immediate use will be the exploration of terrain mapping. In close coupling with the image processor group, range, and slope of a segmented image will allow a terrain map to be constructed, which may be abstracted by the vehicle knowledge system for long-range guidance. Other application areas include route exploration or surveying, obstacle ranging, and as an additional input for close-range navigation. This includes cooperative behavior, such as vehicle following, or additional close-range navigation data. Because of the optical power of the system, target illumination work can also be entertained. Of particular interest is the fact that the laser strike can also be imaged by the video system, conditional upon light level and the variable field of view.

Issues in sensor control, sensor data fusion, sensor registration, tactical deployment, and hierarchical control are all of interest, but the basic sensor platform is immediately useful for more direct experimentation. Reserve space and load capacity are available for the addition of other sensor groups; stereo vision, FLIR, radiation detectors, and antenna systems.

Selected Specifications

Sensor Platform

Elevation	7.5 to 12 feet in 4 seconds
Lift Capacity	1200 pounds maximum
Turntable Slew Rate	700 degrees/second maximum
Positioning Accuracy	2 minutes of angle

Video System

Pulnix TM540 Gray Level Camera	510 x 492 pixels
Sensitivity	3 lux
Optical field of view	43 (wide) to 8 degrees (zoom) Computer controlled auto-iris and focal length
Pitch Range	-45 to +90 degrees
Pitch Rate	320 degrees/second maximum
Roll Range	-90 to +90 degrees
Roll Rate	80 degrees/second maximum
Positioning Accuracy	2 minutes of angle
Current Image Processor	Matrox MAP and MIP suite

Laser Ranging System	Laser Photonics YCF 113
Minimum Range	30 meters (0 meters in modified offset mode)
Maximum Range	30 kilometers
Laser Discharge Rate	30 Hz maximum
Mirror Pitch Rate	900 degree/second typical (15 degree displacement)
Mirror Pan Rate	500 degree/second typical (15 degree displacement)
Positioning Accuracy	1 minute of angle

Point of Contact

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Naval Ocean Systems Center
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San Diego, California 92152

3.3.9 Experimental Near-Infrared Ranging System

An experimental near-infrared ranging sensor based on the concept of return signal intensity is being developed by Jon Connell at the Massachusetts Institute of Technology. When completed, the device will attach to the gripper of a manipulator mounted on a mobile robotic platform and will aid in the grasping of objects. The sensor system consists of two near-infrared light-emitting diodes (LEDs) mounted a known distance apart, with a single phototransistor detector. The LEDs are fired in sequence at a target of interest, and the reflected energy from each one is detected by the phototransistor and measured by an analog-to-digital converter. By the inverse square law, the recorded intensity is inversely proportional to the square of the roundtrip distance traveled.

Furthermore, the difference in the resulting intensities caused by the offset in the distance between the IR emitter can be used to solve for the range value:

$$r = d / \sqrt{(B1/B2) - 1}$$

where r = the range to the target
 d = the distance between emitters
 $B1$ = intensity of return for LED 1
 $B2$ = intensity of return for LED 2.

$B1$ and $B2$ are the brightness or intensity of the returned signals for each of the respective sources. The basic assumptions made in the design are that all surfaces are Lambertian in nature and that the observed objects are wider than the field of view of the LEDs. Ambient light interference is reduced by blinking the LEDs and synchronizing the detector to look for this on and off sequence of energy returning from the observed scene.

3.3.10 Laser Time-of-Flight (TOF) Ranger

Work performed at the Australian National University produced an infrared laser range scanner using time-of-flight methods for three-dimensional scene analysis of a robotic environment. The system consists of a 2.5-watt Hamamatsu pulsed laser which emits infrared pulses at a cycle rate of 10 kHz. The corresponding detector is an RCS type C31034 photomultiplier with high sensitivity and excellent response in the infrared range. This arrangement proved to be relatively economical in comparison with phase modulation type laser rangefinding systems (reference 26). The sensor was designed for use at ranges up to 4 meters and achieved an accuracy of $\pm 1/4$ centimeters over that range when 100 samples per point were obtained.

The system also was given a scanning capability implemented through use of high speed galvanometer-driven mirror components. By sacrificing accuracy, a 64- by 64-element range picture could be obtained within 4 seconds by scanning when only 10 samples per point were obtained. A low-power continuous wave laser emitting in the visible red spectrum was incorporated into the sensor system for use in associating range data with image data for scene analysis.

3.3.11 Laser-Based Scanning Rangefinder

Researchers at Case Western Reserve University have developed a compact, scanning laser rangefinder which measures distance by triangulation (reference 61). Intended specifically for use in robotic applications, the sensor incorporates a solid-state continuous wave laser with a position-sensitive photodetector. The scanning action is generated by the sweep of a mirror which transmits the beam in a plane. The reflected energy is collected by a synchronized receiving mirror offset from the transmitting mirror and then relayed to the photodetector through a focusing lens. Range is determined by inserting the known or measured values into the equation:

$$R = 1/2 B \tan \theta$$

where R = range to the target
 B = baseline distance between mirrors
 θ = angle of incidence of the laser source.

3.3.12 Laser Rangefinding for Robotic Vehicles

Work performed in the mid-1970s at the Jet Propulsion Laboratory for fast, accurate rangefinding remains important even today. The computer-controlled laser sensor ranges by time of flight and was designed to provide collision avoidance and surveying capabilities to the Mars Rover planetary surface explorer. The sensor incorporates a solid-state infrared laser with a gallium arsenide photo-cathode detector responsive in the infrared spectrum. The laser beam is scanned across the field of view by a gimbaled mirror system and obtains approximately 10,000 measurements per second. The rangefinder is effective within the ranges of 1 to 30 meters, and is theoretically capable of ranging out to 100 meters in ideal conditions (reference 62).

3.3.13 Wide Field-Of-View (FOV) Laser Rangefinder

An experimental scanning laser rangefinder developed at Rutgers University uses active triangulation to create a robotic sensor capable of wide-field viewing. The sensor consists of a He-Ne laser transmitting at a wavelength of 632.8 nanometers and an RCA 4840 photomultiplier single element detector with an optical bandpass filter to minimize ambient lighting effects (reference 63). The laser and detector are housed in individual scanning mechanisms separated by distance along one of the axes of rotation and mechanically synchronized to move in unison. Scanning takes place in two dimensions and is based on spherical coordinates. Besides calculating the range for individual points, the system also generates a display of the overall range picture using pseudocolor coding, where different colors represent relative range. The sensor is capable of observing a maximum of 500 pixel elements per second and can range out to approximately 300 inches.

3.3.14 Return Signal Intensity Rangefinder

A monocular ranging technique developed at the Australian National University determines range from the return signal intensity of a pair of light sources (reference 64). The two sources are arranged with a camera detector along a common optical axis which is focused on an object surface. The displacement between the sources will result in differing quantities of returned energy which can be related to distance by the inverse square law of beam energy. The experimental system developed for evaluation of the technique used slide projectors as the light sources. Sensitivity improved as the distance between the lights increased. Although the system is capable of measuring range over uniform, textured, or colored surfaces, it encountered difficulty when observing multicolor nonplanar targets.

3.3.15 Obstacle Avoidance for Mobile Robots

Work performed at Rensselaer Polytechnic Institute for the Defense Advanced Research Projects Agency (DARPA) resulted in a prototype scanning laser triangulation system for obstacle detection and avoidance. The operational sensor (originally designed for the Mars Rover project but shifted to DARPA's Adaptive Suspension Vehicle effort at Ohio State) consists of a solid-state pulsed laser mounted on a continuously rotating mast. The laser is scanned across the ground from 1 to 3 meters in front of a vehicle through the incremental rotation of the mast in azimuth and the step-wise rotation of an eight-sided directional mirror in elevation. The image of the scanned beam is detected by a linear array of 20 photodiodes also mounted on the revolving mast. Detection of and ranging to obstacles in the vehicle path is done by triangulation (reference 65).

3.3.16 Laser-Based Hazard Detection Sensor

A prototype obstacle detection and avoidance sensor is being developed by Cambridge Robotic Systems for application to the Army's Autonomous Countermine Vehicle Program. The sensor scans a near-infrared laser beam in azimuth by using a galvanometric mirror arrangement which causes the source

to strike the ground 30 meters in front of the vehicle. The scan produces a horizontal straight-line trace on the image of the scene which is detected by a charge-coupled device (CCD) camera. The laser and camera are colocated with a synchronized scan rate of 30 frames per second. As the vehicle approaches an object the sensor trace will initially strike the object at its base where it is in contact with the ground. As the vehicle advances, the portion of the line not falling across the object will illuminate the ground behind it while the line segment in contact with the target will move up the object's surface. This phenomenon will appear in the image of the scene as a break in the once continuous line. The width of the observed discontinuity and its vertical displacement from the original trace are proportional to the width and height of the detected body. If the discontinuity surpasses a threshold value, the object is classified as an obstacle and the vehicle is told to move around it. Height accuracy of the system is about 15 centimeters, while width accuracy is approximately 10 centimeters.

3.3.17 Active Two-Dimensional Stereoscopic Ranging System

ROBART II is a battery powered autonomous sentry robot being used by the Naval Ocean Systems Center in San Diego as a research testbed. An architecture of nine distributed microprocessors makes possible advanced control strategies and real-time data acquisition capability. Numerous sensors are incorporated into the system to yield appropriate information for use in collision avoidance, navigational planning, environmental awareness, assessing terrain traversability, and performing security related functions.

An array of five ultrasonic ranging transducers is installed on the front of the body trunk to provide distance information to objects in the path of the robot (reference 16). The sequentially fired array is controlled by a dedicated microprocessor, which performs all time-to-distance conversions and then passes the range information up the control hierarchy to the scheduling microprocessor. A sixth ranging unit is located on the rotating head assembly, allowing for range measurements to be made in various directions as required.

A stereoscopic vision system provides for additional high-resolution data acquisition, and is the robot's primary means of locating and tracking a homing beacon on the recharging station (figure 38). The system does not represent a true three-dimensional capability, however, in that each of the cameras consists of a horizontally-oriented linear (as opposed to two-dimensional) CCD array (reference 66).

The cameras in effect provide no vertical resolution, but furnish range and bearing information on interest points detected in the horizontal plane coincident with their respective optical axes, 110 centimeters above the floor. This is consistent, however, with the two-dimensional simplified world model employed by the robot, wherein objects are represented by their projection on the X-Y plane, and height information is not taken into account.

A structured light source is employed in conjunction with these stereo cameras for ranging purposes. A 6-V incandescent lamp is pulsed at about a 10-Hz rate, and projects a sharply defined V-shaped pattern across the intersection of the camera plane with the target surface. This greatly improves system performance when viewing scenes with limited contrast. The incandescent source was chosen over an active laser diode emitter because of simplicity, the response characteristics of the CCD arrays, and limited range requirements for an indoor system (reference 67).

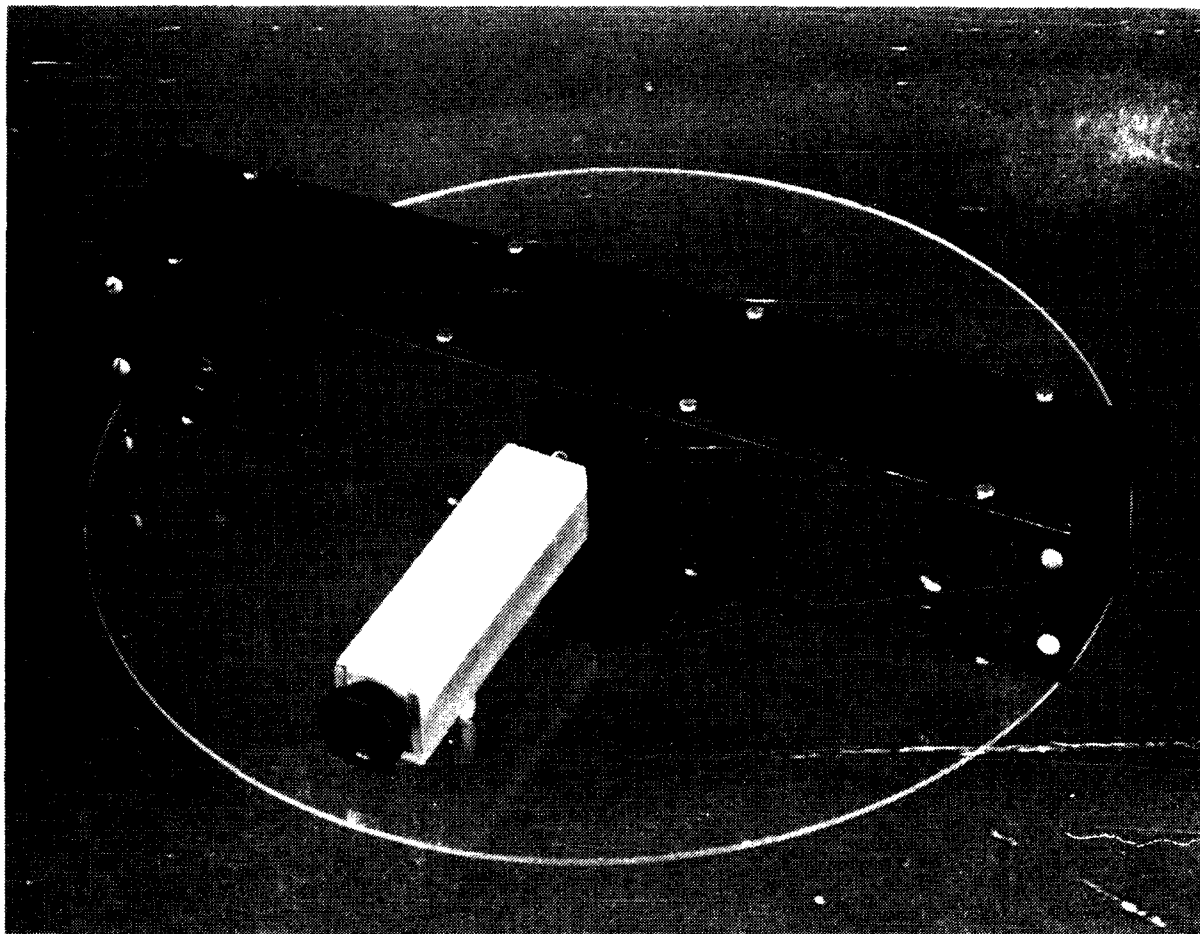


Figure 38. Active Stereoscopic Ranging System used on ROBERT II.

3.3.18 Programmable Near-Infrared Proximity Sensor

A special programmable near-infrared proximity sensor was developed specifically for use on the prototype sentry robot ROBERT II (reference 68), to gather high-resolution geometric information for purposes of navigation and collision avoidance. The primary purpose of the sensor was to provide precise angular location of prominent vertical edges, such as door openings. A Polaroid ultrasonic ranging sensor was used in conjunction with the system to provide range data (figure 39).

An astable multivibrator produces a square wave train of 15-microsecond pulses with a repetition period of 1.7 milliseconds, driving high-power XC-880-A gallium aluminum arsenide LEDs, which emit energy in the near-infrared spectrum. The system uses an array of adjacent LEDs for increased range and sensitivity, with reflected energy focused on the lens of a TIL413 photodiode by a parabolic reflector. The output of this photodiode is passed through a L/C differentiator network, amplified, and then fed to four separate follow-on threshold detector stages. The receiver sensitivity is broken into four discrete levels by these individually adjustable threshold comparators. A strong return will cause all four channels to go low, whereas a weak return will cause only the most sensitive channel to indicate detection. No range information is made available, other than that which can be inferred from the strength of the returned energy.

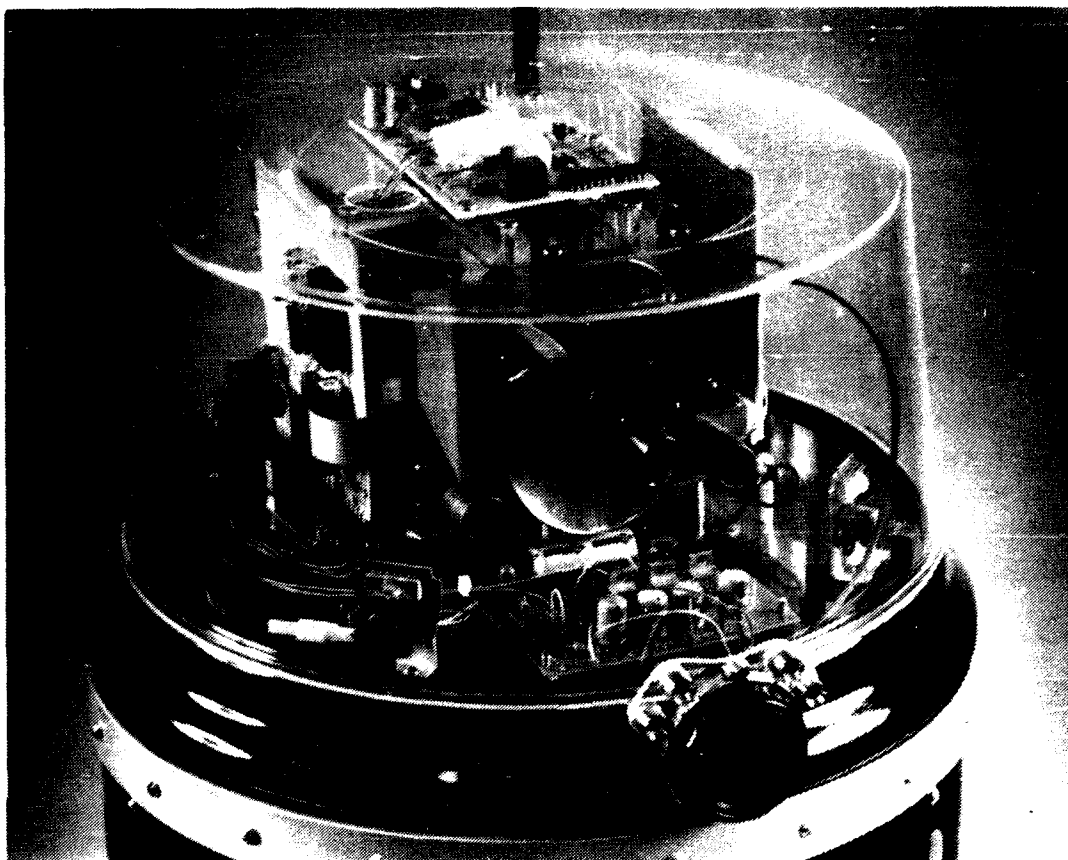


Figure 39. Programmable Near-Infrared Proximity Sensor used on ROBERT II.

Unfortunately, the varying reflectivities of different surfaces preclude signal strength from being a reliable indicator of distance. This turns out to be more a function of surface topography than of surface color; varying surface characteristics create uncertainties that thwart attempts to establish a practical correlation between signal strength and target distance.

Effective range is controlled by firing combinations of LEDs; thereby emitting regulated amounts of energy (i.e., the more LEDs illuminating the scene, the farther the detection range). The number of LEDs in the array that are enabled at any give time is specified by a microprocessor, providing programmable control over the amount of emitted energy (the total number of active emitters can be any value between one and four.) This in turn fixes the maximum range of the sensor. The robot "feels" around out to a distance of 5 or 6 feet, and notes those regions that are obstructed. Then the range of the sensor is extended a few more feet, and those areas that showed no reflected energy are probed again. This process is repeated at computer speed until the sensor has mapped the entire region out to its maximum possible range.

Experimental testing showed the system capable of seeing out to an average of 6 feet with one LED active, 10 feet with two LEDs active, 13 feet with three, and a maximum average range of 15 feet attainable with all four. The data protocol employed for communicating the information to the robot is of the form of a single byte in which the upper nibble represents the number of LEDs that were fired before a reflection was observed, and the lower nibble represents the number of comparators in the receiver threshold detection stage that responded to the returned energy.

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